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Decentralized energy in India and its synergies with Water-Energy-Food security (WEF) nexus

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Varun Gaur

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Referent: Prof. Dr. Joachim von Braun

Koreferent: Prof. Dr. Michael Grimm

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Abstract

The majority of rural Indian households remain dependent on traditional, inefficient and harmful household energy technologies. Rural households make their energy decisions with respect to the Water-Energy-Food security (WEF) nexus jointly, however, previous research initiatives have analyzed household energy access problem in isolation. Taking this WEF nexus into account, this thesis investigates factors influencing household energy transition and identifies an optimal village energy system (VES) for the rural communities in Uttar Pradesh, India. The thesis also analyzes the distributional impacts of VES on different categories of rural households.

Using detailed household survey data, Logit and Zoib (zero one inflated beta) regression techniques were applied to analyze household's activities and to identify factors influencing household energy transition. The results showed that regular non-agricultural income of household's male member increases the probability of household's modern cooking energy and modern lighting transition by 8.6% and 13.6%, respectively. It was found that household's higher agricultural dependence and resource endowments (more labor and cattle) lead to higher share of traditional bioenergy consumption in the total cooking energy mix. Proximity to markets and high household income were observed to positively influence household modern cooking and lighting transition. Local institutions such as local bio-energy markets and barter trade for labor- bioenergy were observed to have significant influence on household energy choice. Results also showed that government's policy instrument such as household connection to government LPG scheme is associated with 20.5% increased probability of household using modern cooking energy as its primary cooking fuel. Results also indicated that social factors such as higher female education and young age of household head are associated with household's increased modern cooking energy consumption in its total cooking energy mix.

The thesis utilized linear optimization technique to formulate a village energy model in GAMS (General Algebraic Modeling Software). The model identified an optimal Village Energy System (VES) considering all possible energy sources and technologies (energy systems) as well as their linkages with food security. Results confirmed energy systems interdependencies for the rural communities. For instance, results showed that the levelized cost of electricity generation from biomass gasifier power system is 2.54 INR/ MJ as compared to 2.89 INR/ MJ from grid electricity-battery based power system. However, model selected the latter for fulfilling village's night time power needs while it assigned higher shadow price of 0.143 INR / MJ to the former. This happened because possible utilization of gasifier power system was expected to create scarcities of local bio-energy resources, resulting in costlier cooking energy system for the village. It was found that DES (Decentralized Energy System) provides demand side energy management opportunities with different energy prices at different timings of the day. Results also showed that high cost of finance deters possible adoption of renewable power technologies, such as solar power.

Lastly, the thesis constructed an agricultural household model linked with VES to analyze VES's welfare consequences on rich and poor households. Here, household had the opportunity to purchase VES's energy services and sell its bio-energy feedstocks to VES. For the poor household, this interaction with VES led to its increased agricultural production with around 22% increase in its farm area cultivation in summers, as well as led to reduction in its off-farm labor by around 11% which is then utilized in its own agriculture. Overall, this interaction resulted in around 4% increase in poor household's annual income. On the down side, this interaction led to poor household shifting towards dirtier cooking energy technologies, resulting in increased external costs and CO_2 emissions by around 27% and 45%, respectively. On the other hand, VES did not impact rich household's food production and only marginally increased its economic gain. However, it led to rich household shifting towards cleaner cooking energy thereby resulting in reduction of its external costs almost by half.

Dezentrale Energie in Indien und ihre Synergien mit der Wasser-Energie-Nahrungsmittelsicherheits (WEF) Nexus

Zusammenfassung

Die Mehrheit der ländlichen indischen Haushalte ist auf traditionelle, ineffiziente und schädliche Haushalts-Energietechnologien angewiesen. Die Entscheidungsprozesse ländlicher Haushalte, wie Energie genutzt wird, wird in Bezug auf der Nexus Wasser-Energie-Nahrungsmittelsicherheit (WEF) getroffen. Jedoch haben die früheren wissenschaftlichen Analysen die Probleme des Energiezugangs von Haushalten selektiv und isoliert betrachtet. Unter Berücksichtigung des WEF-Nexus untersucht diese Arbeit Faktoren, die die häusliche Energiewende beeinflussen und entwickelt ein optimiertes Dorfenergiesystem (VES) für ländliche Gemeinden in Uttar Pradesh, Indien. Weiterhin analysiert die Arbeit die unterschiedlichen Auswirkungen des VES auf arme und reiche ländliche Haushalte.

Mit Hilfe detaillierter Haushaltsumfragedaten wurden die Regressionsverfahren Logit und Zoib (zero one inflated beta) angewandt, um die häuslichen Aktivitäten zu analysieren und Faktoren zu identifizieren, welche die häusliche Energiewende beeinflussen. Die Ergebnisse zeigten, dass das regelmäßige nicht-landwirtschaftliche Einkommen des männlichen Haushaltsmitgliedes die Wahrscheinlichkeit, dass der Haushalt moderne Kochenergie und moderne Beleuchtung nutzt, um 8,6% bzw. 13,6% erhöht. Eine höhere landwirtschaftliche Abhängigkeit und die Ressourcenausstattung des Haushalts (mehr Vieh und Arbeiter) führen zu einem höheren Anteil des traditionellen Bioenergieverbrauchs am Kochenergiemix. Die Nähe zu den Märkten und das hohe Haushaltseinkommen haben sich positiv auf den Übergang zu modernen Haushalts-Energietechnologien ausgewirkt. Lokale Einrichtungen wie Bioenergiemärkte und der Tauschhandel (Arbeit für Bioenergie) haben einen signifikanten Einfluss auf die Energiewahl im Haushalt. Die Ergebnisse zeigten auch, dass das politische Instrument der Einbindung an das staatliche LPG-System zu einer um 20,5% höheren Wahrscheinlichkeit führt, dass der Haushalt moderne Kochenergie als primären Kochbrennstoff verwendet. Die Ergebnisse deuteten auch darauf hin, dass soziale Faktoren wie eine höhere Bildung von Frauen und ein junges Alter des Haushaltsvorstehers zu einem höheren Anteil moderner Energien am Kochenergiemix führen.

Die Dissertation verwendet eine lineare Optimierungstechnik, um ein Dorf-Energiemodell in GAMS (General Algebraic Modeling Software) zu formulieren. Das Modell wählt ein optimales Village Energy System (VES) unter Berücksichtigung aller möglichen Energiequellen und Technologien sowie der Kopplung des Energiesystems mit der Ernährungssicherheit. Die Ergebnisse bestätigten die gegenseitigen Abhängigkeiten der Energiesysteme für die ländlichen Gemeinden. Die Ergebnisse zeigten zum Beispiel, dass die Stromgestehungskosten aus dem Biomassevergaser-Stromversorgungssystem 2,54 INR / MJ betragen, verglichen mit 2,89 INR / MJ aus dem Netzstrom-batteriebasierten Stromsystem. Das Modell entschied sich jedoch für Letzteres, um den nächtlichen Strombedarf des Dorfes zu decken, während es dem anderen System einen höheren Schattenpreis von 0,143 INR / MJ zuwies. Dies ist darauf zurückzuführen, dass eine mögliche Nutzung des Vergaserstroms dazu führen kann, dass Knappheiten lokaler Bioenergieressourcen entstehen, was zu einem teureren Kochenergiesystem. Es wurde festgestellt, dass DES (Decentralized Energy System) nachfrageorientierte Möglichkeiten des Energiemanagements bietet. Die Ergebnisse zeigen auch, dass hohe Finanzierungskosten eine mögliche Einführung erneuerbarer Energietechnologien verhindern.

Abschließend entwickelte die Arbeit ein landwirtschaftliches Haushaltsmodell in Verbindung mit VES, um die Auswirkungen von VES auf reiche und arme Haushalte zu analysieren. Hier hatte der Haushalt die Möglichkeit, VES-Energiedienstleistungen zu kaufen und seine Bioenergie-Rohstoffe an VES zu verkaufen. Bei einem armen Haushalt führte diese Interaktion zu einer Steigerung der landwirtschaftlichen Produktion (ca. 22%) und einer Reduzierung der landwirtschaftlichen Arbeit in fremden Betrieben um ca. 11%. Alles zusammen führte zu einem Anstieg des Jahreseinkommens des armen Haushalts um ca. 4%. Andererseits führte dies dazu, dass die Kochenergietechnik armer Haushalte schmutziger wurde was zu erhöhten externen Kosten führte (ca. 27%). Demgegenüber wurde die Nahrungsmittelproduktion reicher Haushalte von VES nicht beeinflusst und erhöhte nur geringfügig den wirtschaftlichen Gewinn. Jedoch verlagerten sich reiche Haushalte in Richtung sauberer Kochenergien, wodurch die externen Kosten um fast die Hälfte reduziert wurden.

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List of Abbreviations

AHM	Agricultural Household Model
Ah	Ampere hours
AY	Ayera village
BAU	Business-as-usual scenario
BM	Bhoye Mau village
BPL	Below Poverty Line
CEA	Central Electricity Authority
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DALYs	Disability-adjusted life years
DES	Decentralized Energy System
FGD	Focussed Group Discussion
GAMS	General Algebraic Modeling System
GW	Gigawatts
HH	Household
INR	Indian Rupees
KW	Kilo Watt
kWh	Kilo Watt hours
LPG	Liquified Petroleum Gas
LL	Lalwara village
MNRE	Ministry of New and Renewable Energy
MG	Manjharia Ganga village
MH	Mohammadpur Hayak village
MP	Manchitpur village
m^3	Cubic meter
NSS	National Sample Survey
NPV	Net Present Value
NSSO	National Sample Survey Organization
NV	Nagla banveer village
OK	Oonkhas Village
PDS	Public Distribution System
PM2.5	Particulate Matter 2.5
PTEM	Physical-technical-economic models
PV	Photovoltaic
SHS	Solar Home Systems
SWP	Solar Water Pump
TERI	The Energy and Resources Institute
TSP	Total Suspended particles
UP	Uttar Pradesh province of India
VES	Village Energy System
WEF	Water-Energy-Food Security Nexus
ZOIB	Zero-one-Inflate Beta regression

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CHAPTER 1

1. INTRODUCTION TO THE RESEARCH

1.1 Background

Census of India 2011 indicates that around 70% of the Indian population lives in rural areas (Bhattacharya SC 2015, Kumar A et al. 2015). Rural development is therefore very much important for India's sustainable development. Modern energy supply is an important aspect for the sustainable economic development in rural areas (Mirzabaev et al. 2015, Kaygusuz 2011) due to its potential in reducing poverty (Ewing and Msangi 2009), contributing positively to environmental sustainability (Pacala and Socolow 2004), facilitating improved health conditions by reducing indoor air pollution (Wilkinson et al. 2009), enabling women empowerment (Mirzabaev et al. 2014) amongst other relevant factors. Strengthening modern energy supplies in rural areas is therefore an important driver for promoting country's sustainable development. Currently, traditional biomass is a major source of energy in rural India. It is estimated that around 836 million people lack access to modern cooking systems in India (Rehman et al. 2012) and are majorly dependent on traditional biomass for thermal applications. These are majorly unprocessed biofuels, such as fire wood, crop residues and animal dung with firewood forming the biggest percentage (Hiloidhari et al. 2014, TERI 2010). Moreover, recent studies indicate that during 1999-2000 to 2009-10, there has been an increase in firewood consumption by about 7.5 percent (Sehjpal et al. 2014). Further about 45% of India's 168 million rural households are un-electrified (Harish et al. 2014). Hence, India faces an enormous rural energy poverty challenge which has negative consequences to its sustainable development.

Modern energy such as modern bioenergy can offer several opportunities for sustainable development in India, however, its utilization has complex linkages with food security, land and water use, and other economic activities of households (Mirzabaev et al. 2015). These linkages may result in complex tradeoffs and negative externalities or may also offer positive synergies. For instance, in India, around 64% of the rural population depends on firewood for cooking energy needs (Hiloidhari et al. 2014) and this affects their time allocation for farm production (Barnes and Floor 1996, van der Kroon et al. 2013). Modern energy utilization can bring down the time spent on collecting fuelwood and the time saved can be utilized for any other productive activity (Heltberg 2004). Further, around 26% of the Indian rural population depends on cattle dung and crop residues for household energy needs (Hiloidhari et al. 2014) annually consuming around 300 to 400 million tonnes of cattle dung for cooking (Rasul 2014). Such diversion of animal wastes from fertilizer use to fuel use, can negatively affect the agricultural production (ibid). On the other side, promotion of efficient modern energy such as biogas-based cooking or power generation could allow for increased use of animal dung as fertilizer, thereby strengthening food security. Crop residues can also be used for biomass gasifier-based power generation, but this may also result in scarcity of crop residues for cooking energy or for livestock feed. Traditional use of biomass for cooking or kerosene for lighting also has detrimental health effects through indoor air pollution (Lim and Seow 2012, Duflo et al. 2008), which further leads to low productivities amongst the households, besides increasing their health care costs, aggravating their poverty. For instance, in India, the number of DALYs (disability-adjusted life years) caused by solid fuel related indoor pollution is 8 million per year (World Bank 2013), and the burden of disease attributable to domestic fuel use is ~6% of the total national disease burden (Andresen et al. 2005). Energy also plays a very crucial role for water utilization in food production. For instance, in India, 63-70% of its irrigation needs are met by pumping ground water (Rasul 2014, Shah et al. 2006). In 2003–04, around 12.8 million electric water pumps with a total load consumption of 51.84 gigawatts (GW) consumed 87.09 billion kilowatt-hours of electricity for ground water irrigation in India (ibid). However, supply and quality of power is a big issue across India (Palit et al. 2013, Sinha et al. 2006) with power being available for only few limited hours and that too in the night time in rural areas. Further, electricity for agriculture is a big political issue in the country with electric utilities being forced to provide free or highly subsidized electricity for water pumping, leading to inefficient water usage by farm households (Sinha et al. 2006). The low recovery of electricity bills forces electric utilities to make load shedding, thereby affecting farm irrigation, household education, household health, other productive activities in the villages. Groundwater market is another important aspect of Nexus, where the small and marginal farmers are dependent on large landholders (pump owners) for irrigation water and pay significantly higher costs. On the other side, modern decentralized energy technologies such as solar or bioenergy-based pumps can provide cheap, clean and reliable power and facilitate efficient water utilization, thereby strengthening food productivity and food security.

The above discussion stresses upon the urgent need for India to strengthen its modern energy supply. Further, it shows that there exists high degree of interdependency between energy, food security and other natural resource utilization of households where modern energy development can create synergies between different activities of the households but can also result in complex tradeoffs.

1.2 Problem Statement

The available literature on the household energy access revolves around the determinants of household's modern energy transition, energy development strategies for the rural households, and the cost benefit analysis of modern energy adoption by households. These aspects are briefly discussed below along with their research gaps.

Determinants of modern energy transition

There is a vast body of literature which has analyzed the factors influencing households' transition from traditional to modern energy usage in India and in other developing countries (Isaac and van Vuuren 2009, Devi et al. 2009, P. Komala et al. 2014, Burke and Dundas 2014, Sehjpal et al. 2014, Alem et al. 2016, Rahut et al. 2016). Using consumer utility maximization behavior of households, these studies found that the household's energy choices are greatly influenced by various technical and socioeconomic factors such as its income level, size, education, occupation, gender, head's age, access to clean energy sources, household standard, amongst others. Howells et al. 2010, Srivastava et al. 2012 and Lee et al. 2015 further discussed the impact of institutions, information failures, other external factors that influence the household energy decisions. Ekholm et al. 2010 extended the dimensions of energy choice study in India by considering heterogeneity of consumers. In addition, there also exists several studies which have tried to improve the robustness of econometric techniques for analyzing household energy choices (Alem et al. 2016, Burke and Dundas 2014, Rahut et al. 2016). While most of the Indian studies have been pan national studies based on NSS (Indian National Sample survey) or Indian Human Development Survey, some of the following studies such as Devi et al. 2009, P. Komala et al. 2014, Sehjpal et al. 2014 utilized household surveys to analyze the household energy choice in specific regions of India. There have been diverse attempts to analyze the energy choice of the households. However, while analyzing household's traditional bioenergy consumption, they concentrated on household's consumption side only (following consumer-utility maximization principle) but missed to consider the supply side of household (for instance, household bio fuel production) and interconnection between different household activities. This is crucial as rural household is both the supplier and consumer of bioenergy. For example, household's decision to use cattle dung cake for cooking energy is also dependent on its time allocation for livelihood generation, and on its decision to use cattle dung as fertilizer input for agricultural production. Recent literature has highlighted the lack of a holistic approach in understanding the energy transition of households (Kowsari and Zerriffi 2011) and ibid has argued that the previous studies have adopted techno-economic approach, psychological approach and sociological approaches in understanding the energy transition of rural households but the integrated approach that combines all the above approaches have been very limited or missing. Mirzabaev et al. 2015 argues that the application of Water-Energy-Food Security (WEF) Nexus approach, which analyzes household's activities and interconnections, can be used as an integrated approach to understand household behavior on energy consumption.

Energy development strategies for rural communities

Several studies have supported the notion that decentralized energy planning is an apt solution for eradicating energy poverty in rural India (Hiremath et al. 2010). Therefore, it is very important to find suitable strategies for designing optimal decentralized energy systems. It is argued that decentralized energy system (DES) for a community could be a better approach than the DES for a single household because there exist several modern energy technologies such as biomass gasifiers (crop or wood residue based) which have great potential in rural India (PWC 2016, Palit et al. 2013) and particularly in Uttar Pradesh whose 2/3rd of population is involved in agriculture (University of Allahabad 2015), however this technology needs a minimum plant load factor for its technical as well as financial viability (Palit et al. 2013). Therefore, such technologies are more suitable for a village cluster rather than individual households. Palit and Sarangi 2014 argues that if community-based approach can be combined with entrepreneurship model in running energy systems, then DES for a village cluster has a great potential in rural India. In the literature, two strategies have often been applied for modelling optimized decentralized energy systems. Firstly, there are studies that utilize off-the-shelf hybrid energy system modelling softwares such as HOMER, RETSCREAN, MARKAL, LEAP etc (Sen and Bhattacharya 2014, Kobayakawa and Kandpal 2014, Hafez and Bhattacharya 2012, etc.). However, most of them are capable of only modelling the electricity supply systems with few limited renewable power technology options and only few are capable of modeling thermal and irrigation systems (Sinha and Chandel 2014, Sen and Bhattacharya 2014). Even the tools capable of modeling thermal systems, mainly emphasize on household air heating, which is often modeled in isolation to the power system. Modeling electricity system in isolation to cooking energy system is not a good approach because bio-energy feedstocks such as crop residues can be used in both power and thermal systems. Few optimization software such as MARKAL are generally used in large and regional scales with very limited applications in local scale. Secondly, there exist studies that utilize their own customized optimization models for modeling the decentralized energy systems (Herran and Nakata 2012, Patil et al. 2010, Deshmukh and Deshmukh 2009, Hiremath et al. 2010, etc.), using objective functions such as minimum system costs, minimum level of emissions stemming from system operation etc. For instance, Patil et al. 2010 utilizes linear optimization model to develop an integrated renewable energy system for a village cluster in Uttarakhand, India. Assuming the entire village cooking energy demand being met by biogas, the study modeled the village electricity considering selected renewable energy technologies. However, like this study, most of such literature have several gaps. Firstly, most of these studies are focused on electricity systems considering few limited energy resources and technologies. Secondly, most of such literature do not consider the interdependencies between lighting, power, thermal and pumping energy systems in terms of common energy feedstocks or other inputs where, for instance, limited bio-energy feedstocks can be used for different end use applications. Almost all the above discussed literature failed to include the interdependencies that exist between energy utilization and food security of the households, for instance, cattle dung besides being an important energy feedstock is also an important farm fertilizer, or the crop residues besides being used an energy feedstock, is also used as an important livestock feed. Given the fact that there exists interdependencies among energy production (& utilization), food production and natural resource utilization at the household or community level, the above research papers studied bio energy/ renewable energy development in complete isolation. Thus, there is a need to develop a suitable village energy model that can identify an optimal energy system for the rural community while considering energy systems interdependencies and its linkages with food security.

Cost benefit analysis of the energy system adoption by households/ communities

The above discussed village energy modelling tools also lack their interaction with the agricultural village households although it is important to analyze the implications of such village energy system on the household's general welfare. For instance, if the household contributes its bioenergy resources to the village energy system (VES) and receives its cheap & reliable energy, then this contribution may impact household's own bioenergy usage for fertilizers, livestock feed or other economic activities. Therefore, village energy system will not only impact household in its energy utilization sphere but also in its food production and its water utilization such as irrigation. However most of the research studies in this category have ignored this nexus (Chauhan and Saini 2016, Alfaro and Miller (2014), Bhandari et al. 2016, Kobayakawa and Kandpal 2014, Hafez and Bhattacharya 2012, Herran and Nakata 2012, Patil et al. 2010, Deshmukh and Deshmukh 2009, Hiremath et al. 2010). Moreover, there exist studies that have utilized economic models (such as computable general equilibrium or partial equilibrium models) to analyze the impact of bioenergy production on the livelihoods of households (Gebreegziabher et al. 2013, Bryngelsson and Lindgren 2013, Hausman et al. 2012). However, most of these studies lay focus on liquid biofuels and are macro level studies. Further, Djanibekov & Gaur 2016 argues that the existing studies on the topic lacks the analysis of distributional effects of modern renewable energy / bio-energy development as well as fail to include heterogeneities within households. An agricultural household model that utilizes the interconnection between different economic activities of the households such as its production and consumption decisions, will be an apt choice to address the above required modeling issues. Pattanayak et al. 2004, Chen et al. 2006, Guta, 2015 are some studies that have used agricultural household model to analyze the bioenergy-based decisions of households but focused on only econometric estimations and missed ex-ante assessments (Djanibekov et al. 2016) and did not consider the heterogeneity within and among households (ibid).

1.3 Research Questions

Based on the above discussions (problem statements), following research questions are posed:

Research Question 1: To analyze household's activities and to identify the drivers that impact its transition from traditional energies to modern energies of different kinds? More specifically, what are the technical, economical, behavioral, psychological, social, anthropological and environmental factors that drive the household to make transition from traditional energies to modern energies of different kinds?

Research Question 2: How does a village community/ village energy enterprise choose an appropriate village energy system (VES) for meeting village's power, cooking, lighting and irrigation energy demands?, considering: (a) all possible energy technologies and available energy resources (energy systems), (b) energy systems interdependencies in terms of common limited feedstocks and inputs, (c) boundaries that it does not encroach upon the food security of the participating community, (d) demand side management opportunities.

Research Question 3: Considering the interdependencies between different household activities, how does the adoption of the above village energy system (VES) impact the welfare of its participating households? What are the net gains and losses for the households participating in the VES? What will be the distributional impacts of such VES on village's rich and poor households, respectively?

1.4 Methodology

This section briefly discusses the data source and the research methodology for answering the research questions.

a) Data Source

The Indian province of Uttar Pradesh (UP) was selected for this study as this province has one of the highest dependency on traditional bio-energy based household cooking in the country (NSSO 2015) and is an agricultural dominant economy (University of Allahabad 2015). Also, UP has one of the lowest electrification rates in the country (Census of India 2011). To answer the research questions, a field research (household and village surveys) was conducted in Uttar Pradesh in year 2015. Considering the variance of socio economics and energy systems in the province, sampling techniques were used to select around 400 households from 9 villages and 5 districts in UP. The field research collected information on household demography, incomes, expenditures, asset endowments, agricultural production, and energy use. Village surveys were also conducted to understand villages' energy supply-demand and socio-economic characteristics.

b) Research Methodology

Thesis utilizes the following methodologies for answering the respective research questions:

For Research Question 1, thesis utilizes an integrated approach, as suggested by Mirzabaev et al. 2015 and Kowsari and Zerriffi 2011, which combines the following 3 different approaches for understanding factors influencing household energy transition: 1) physical-technical-economic models (PTEM) which which include economic models that assume household to take energy decisions based on its utility maximizing behavior and technology models where changes in household energy usage pattern arise from the change in energy technologies, 2) psychology based approaches which suggest that household energy use decisions involve complex behavioral and social processes, 3) Sociological and anthropological model involving institutions and external factors in household's decisions. Utilizing the above discussion and the learnings from the field research, potential factors influencing household energy transition are identified in the following categories (Economic, Technical, Social, Behavioral and Cultural, Policies and institutions, households and their interactions with other households). Different econometric techniques such as logit and ZOIB (Zero-one inflated beta) are then used in this study to analyze the impact of above discussed factors on the household energy transition.

For Research Question 2, a linear optimization model is developed in GAMS (General Algebraic Modeling System), where desired outcome of the energy system forms the objective function, while the energy system characteristics and behaviors are modeled as constraints of the model. Based on the field research, least possible energy system cost is used as the objective function of the model. For the case where, desired outcome of the energy system also includes minimum harmful gas emissions, health damage costs are also associated with each participating energy technology. Energy systems interdependencies and its linkages with food security are modeled as a set of constraints.

For Research Question 3, an interaction between VES (discussed in research question 2) and the Agricultural Household Model (AHM) is utilized. In the agricultural household model, production decisions of the household are dependent on its consumption choices, where households try to maximize its utility from consumption of market goods, agricultural staples, commercial energy, household bioenergy, household time endowment, household characteristics and resources subject to its agriculture production, energy production and labor time constraints. This AHM is linked to VES where household can sell its resources to VES and can also buy VES's energy services at predefined rates. Thus, any intervention with the VES will have an impact on household consumption and labor supply (for example the bioenergy use, or the time saved from fuel wood collection) and the AHM captures the direct effect of exogenous changes arising due to interaction between households and the VES. The model is written in GAMS.

1.5 Conceptual Framework

In the literature, energy ladder and fuel stacking are the two theories which have been used to analyze the factors influencing the household energy choices. The theory of energy ladder was an early approach, which is based on the correlation between household wealth and the uptake of modern energy sources (Davis 1998, Barnes and Floor 1996, van der kroon et al. 2013), however, using empirical evidences, several newer studies have challenged this theory (Masera et al. 2000, Heltberg 2004). Fuel Stacking is a more recent approach which says that households may not completely switch from one fuel to another and instead use additional energy type without completely abandoning the energy type which they were using early (ibid, Kowsari and Zerriffi 2011). However, the above-mentioned theories have some gaps. Both the theories assume the household to be a utility maximizing consumer and focus mainly on its consumption side. However, in section 1.1 and 1.2, it was discussed that the household's energy choice is not just dependent on its consumption side but also its production side and the household take its energy related decisions not in isolation but based on its food production and natural resource utilization (WEF Nexus). Building on the above discussions, the conceptual framework used for this study, is shown in figure 1.1 below. It has 4 major depictions. Firstly, at the core, its shows energy systems interdependencies. For the decentralized energy system planning around rural communities, where local energy resources play a crucial role, different households' energy segments such as cooking energy, lighting, power or irrigation energy, are all interdependent. For instance, crop residues produced by households can be used for cooking energy if burnt in traditional/ improved cook stoves, or they can be used in biomass gasifier for power generation or for irrigation pumping. Therefore, community's electricity supply system may not be modeled in isolation to its thermal energy system. Secondly, at the core, it shows the water-energy-food security nexus around the households/ communities, where energy decisions of households/ communities are also dependenet on their food production or natural resource utilization as discussed before. Thirdly, on the left, it shows that there could be technical, economical, behavioral, psychological, social, anthropological and environmental factors, such as renewable energy promotion schemes etc., which can affect households' use of natural resources, their food production, energy production and consumption. This can result in potential tradeoffs and synergies, with their impacts on food security, poverty reduction, environmental sustainability, labor market, gender equality, health and education. Lastly, it shows that how interactions amongst households can change the outcomes of the drivers. Households are heterogeneous with respect to their economic settings (Ekholm et al. 2010). Therefore, it may happen that decentralized energy interventions may bring different outcomes for different categories of households. Furthermore, households in the rural areas are interrelated to each other through the farming activities either directly or via markets. Hence, the intervention at one type of household may have positive or negative spillover effects on the other category (type) of households. All the above factors can change the outcomes of the drivers. Further, the resulting changes in the outcomes could modify the nature and relative effects of various drivers in the next stage and these changes could also be affected by the spillover effects.

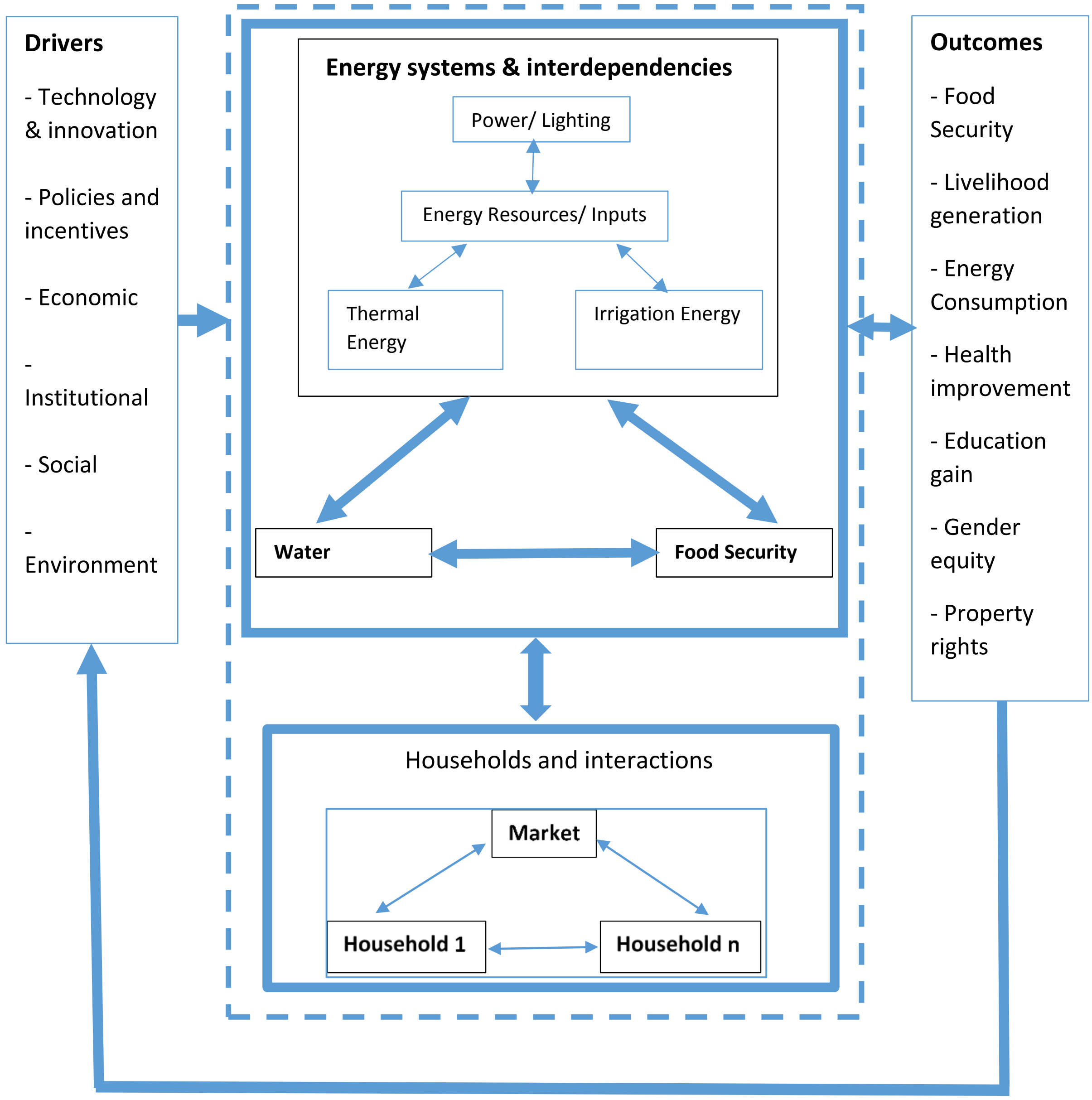

Figure 1.1: Conceptual framework on rural household's energy use
Sources: Adapted and inputs taken from Mirzabaev et al. 2015

1.6 Structure of the Thesis

This dissertation includes 6 chapters. Current chapter 1 provides introduction to the research, identifies research gaps, research questions, research methodology and the conceptual framework under which the research is conducted. Chapter 2 presents the research area and its energy situation, as observed in the field research. Chapter 3 analyzes the factors that impact household's energy choices. It utilizes logit and zoib econometric techniques to analyze the drivers impacting household's transition to different kinds of modern energies. In chapter 4, a village energy model is developed that identifies an optimal village energy system while considering the energy systems interdependencies and its linkages with food security. This also analyzes different scenarios under which the village energy system can evolve. It uses GAMS framework for developing the model. In chapter 5, an agricultural household model is presented which interacts with the village energy system. This model assesses the synergies and the tradeoffs that exists between Village Energy System (VES) and its participating households. Further, it also analyzes the distributional impacts of VES on village's poor and rich categories of households. It uses GAMS framework for developing the model. Chapter 6 concludes and summarize the major findings of this thesis.

CHAPTER 2

2. RESEARCH AREA AND ITS ENERGY SITUATION

This chapter has 5 sections. In section 2.1, research area (i.e. Uttar Pradesh province of India), its characteristics and research's data sources have been described. Section 2.2 presents the narrative on energy situation in each surveyed village, as observed during the field research. In section 2.3, a comparison has been made between government energy statistics on UP and the findings of the field research. Section 2.4 discusses the field research observations on the linkages between household's energy utilization and its WEF nexus. Section 2.5 summarizes the energy situation in each surveyed village.

2.1 Research Area: Uttar Pradesh (UP) province of India

The Indian province of Uttar Pradesh (hereafter referred as UP) was selected for this study. The following 3 reasons make UP an appropriate choice for the research on the Water-Energy-Food Security (WEF) nexus around households. Firstly, National Sample Survey (NSS) of 2011-2012 indicates that amongst all regions in India, UP has the highest dependence on traditional bioenergy for household energy use (NSSO 2015). Secondly, this province has one of the lowest household electrification rates in the country (Census of India 2011). Thirdly, it is an agriculture dominant economy with around 66% of its labor force dependent on agriculture (University of Allahabad 2015) and has one of the largest livestock populations in the country (Ministry of Agriculture 2012).

2.1.1 Strategy for selecting research locations in UP

UP has a population of 199.58 million (Government of Uttar Pradesh website) spread around its 75 districts. Considering confidence interval of 95% for the research outcomes, sample size came out to be around 400 households. To select these 400 households, following 3 sampling steps were undertaken.

Step-1: First step was to select target districts of UP considering the variance of socioeconomics and energy systems in the province. For this task, a district level dataset was created with their following district attributes: per capita net district product (Uttar Pradesh Government 2008), percentage of primary sector (Agriculture, forestry and mining) in Net District product (ibid) , population density (ibid), percentage of households using firewood for cooking (Census of India: Uttar Pradesh 2011), cattle dung for cooking (ibid), crop residue for cooking (ibid), LPG for cooking (ibid), percentage of households using electricity for lighting (ibid), yearly biomass surpluses in the districts (Biomass Atlas of India 2004, Indian Institute of Science, Bangalore), percentage of cultivated area under wheat and rice production (Uttar Pradesh Government 2009) and their respective yields (ibid). On this dataset, a statistical clustering technique was applied, and homogenous district clusters were identified and then 4 districts were chosen randomly from different clusters. These districts along with their characteristics are given below in table 2.1.

Table 2.1: Districts selected for the field research and their characteristics

Selected Districts	Region in UP	Net district domestic Product	Electrification rate	Major cooking energy fuels/ systems
Sant Kabir Nagar	Eastern UP	Low	Low	Crop Residues
Rae Bareilly	Central UP	Low	Low	Firewood
Moradabad	North Western UP	Medium	Medium	Cattle Dung and Firewood
Mathura	West UP	Highest	Highest	High LPG usage

Source: Author's elaboration using numerous sources as discussed in the text above.
Note: While clustering, highest number of districts fell in the poorest cluster of districts, therefore 2 districts Sant Kabir Nagar and Rae Bareilly were chosen from the same cluster

Step-2: Second step was to select villages from these districts. For the above selected districts, the list of their respective villages was drawn from Census of India: Uttar Pradesh 2011 database. With the assumption that all the villages of a district resemble district's characteristics, 2 villages were randomly selected from each district. In this way, 8 villages from the 4 districts were chosen, whose details are given below in table 2.2.

Table 2.2: Villages selected for the field research

S.No	Selected Villages	District	GPS coordinates	Population (Census 2011)	HHs surveyed (Nos)	Distance - city center(km)	Hereafter referred as
1	Manjharia Ganga	Sant Kabir Nagar	N26° 43.518', E 083° 01.883'	224	59	8	**MG**
2	Oonkhas		N26° 48.031', E 083° 03.402'	182	51	3	**OK**
3	Manchitpur	Rae Bareilly	N26° 16.866', E 081° 17.360'	163	40	11	**MP**
4	Bhoye Mau		N26° 11.644', 5E081° 17.916'	242	70	9	**BM**
5	Ayera	Mathura	N27° 34.928', E 077° 51.614'	355	58	13	**AY**
6	Maoli		N27° 32.682', E 077° 42.650'	129	41	22	**MM**
7	Nagla banveer	Morada bad	N28° 48.367', E 078° 39.244'	303	40	14	**NV**
8	Lalwara*		N28° 44.247', E 078° 42.161'	552	70*	16	**LL**

S.No	Selected Villages	District	GPS coordinates	Population (Census 2011)	HHs surveyed (Nos)	Distance - city center(km)	Hereafter referred as
9	Mohammad pur Hayak *	Meerut	N29° 07.049', E 077° 43.330'	50	12	18	**MH**
Source: Census of India 2011 and Author's own field surveys * During the survey in village Lalwara, unexpected heavy rain/ hail storm spoiled the crops in the region which led to farmer's protests (Newspaper: Times of India, March 17,2015) and the field research in the village was affected. To compensate, village Mohammadpur Hayak (MH) of its adjoining district of Meerut was surveyed.							

Step 3: Third step was to select households. For this, systematic sampling technique as suggested by Levy & Lemeshow 2008, was used. Using this, surveyor first went to the center of the selected village, selected a random direction and randomly selected a household in that direction. Thereafter, in the same direction, another household with a certain gap of number of households, was selected. If there were heterogeneous clusters within a village, the same process was done for each cluster to include variations amongst and within heterogeneous clusters within a village. This way around 100 households were selected in total 2 different villages in each district where proportionally more number of households were chosen from the bigger village.

The surveys took place during March 2015 till June 2015. Surveyed UP districts are encircled in the map below in figure 2.1.

Note: Out of the 400 household surveys, data from 380 households is used in this research.

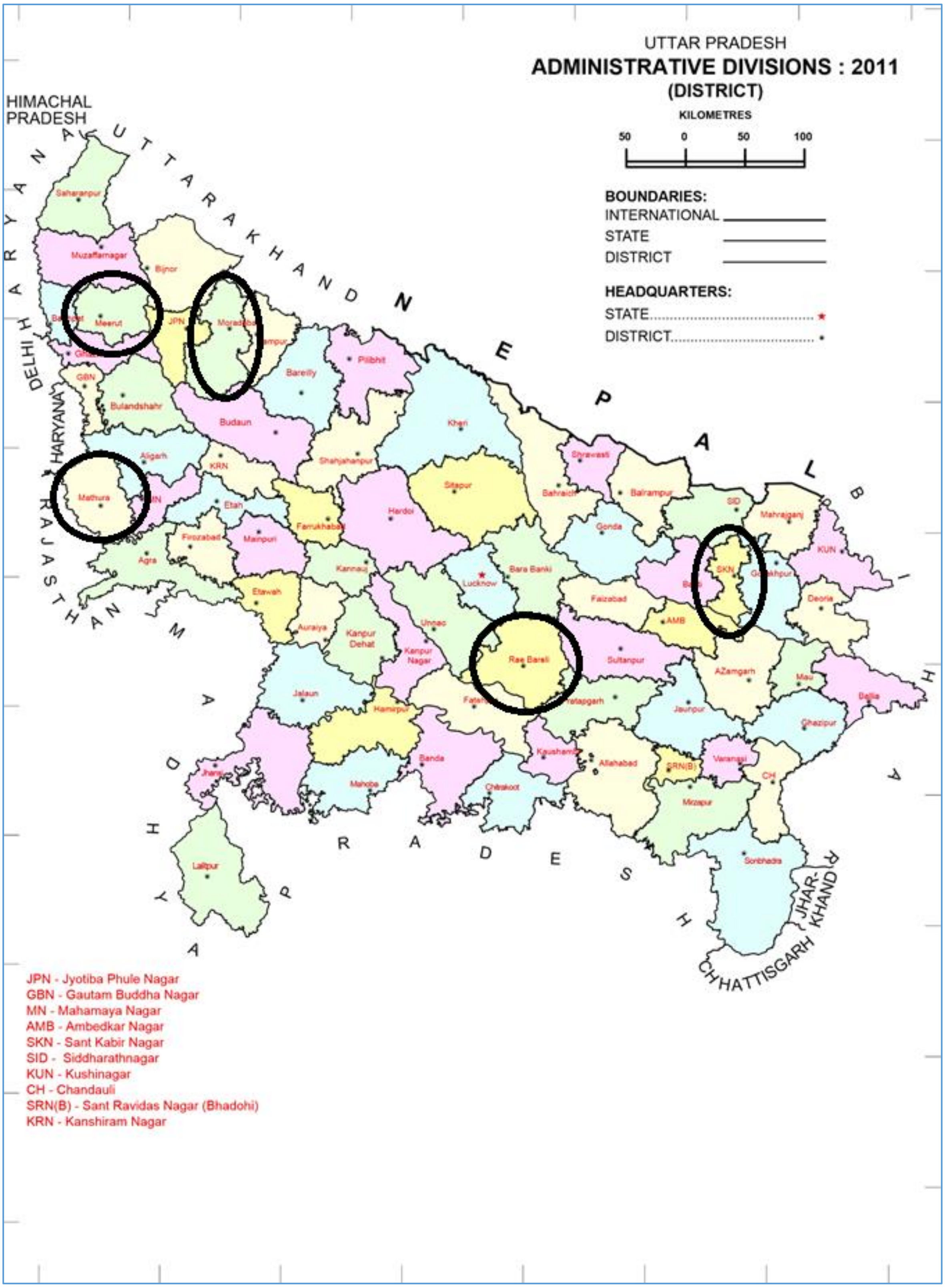

Figure 2.1: Map of Research Area (Uttar Pradesh (UP) with the surveyed districts)

Source: ORGI, Ministry of Home Affairs, Government of India

2.1.2 Energy Statistics of UP from government surveys

Before starting field surveys, a desktop research was conducted to understand the energy situation in Uttar Pradesh districts. Table 2.3 below presents the household energy use statistics in rural UP making use of the data from census of India 2011, National Sample Survey of 2011-2012(NSSO 2015) and Central Electricity Authority (CEA) 2016.

Table 2.3: Uttar Pradesh's energy statistics from government data sources

S.No	**Energy types and their application**	**Percentage of households with primary energy type for the mentioned application**	
		Source: Census of India 2011	Source: National Sample Survey of 2011-2012 (NSSO 2015)
1	Electricity for lighting	23.8%	40.4%
2	Kerosene for lighting	75%	58.5%
3	Solar energy for lighting	0.6%	-
4	Firewood for cooking	54.4%	56.1%
5	Cattle dung for cooking	27.9%	33.4%
6	Crop residue for cooking	10.5%	N/A
7	LPG for cooking	6.4%	6.7%
8	Biogas for cooking	0.1%	-
9	Electricity for cooking	0.1%	-
10	Kerosene for cooking	0.2%	0.01%
11	"Other Fuels" for cooking	-	2.8% (biogas, electricity and charcoal)
S.No	Province level statistic		
1	Percentage of villages electrified	98.7% [CEA (Central Electricity Authority), 2016]	
Sources: Census of India 2011, NSSO 2015, CEA 2016			

Table 2.3 shows that in UP, although village electrification rate[1] is high but the household electrification rate is very poor. For both rural and urban combined, the electrification rate in UP is 36.8% (Census of India 2011), and majority of the rural households are dependent on kerosene for their lighting energy needs. For the cooking energy use, these data sets show that around 7% of rural households in UP use LPG as primary source of cooking energy whereas remaining households use traditional biomass as primary cooking energy. Amongst biomass, firewood is the primary cooking energy source, followed by cattle dung cake. Amongst all the regions in India, NSS 2011-2012 suggests

[1] As per the website of Ministry of Power, Government of India, a village is said to be electrified if the basic infrastructure such as distribution transformer / distribution lines is available in the village, and, at least 10% of its households are electrified, and, any of the public places like Schools, Panchayat Office, Health Centres, Dispensaries, Community centres etc. avail power supply on demand

that Uttar Pradesh has one of the largest household population which use cattle dung cake as primary energy source (NSSO 2015). Concerning biogas, although government has installed around half a million biogas plants in UP between year 1992 and 2014 (Biogas plants, Ministry of New and Renewable Energy, Government of India website), only 0.1% of rural HHs use biogas as primary fuel for cooking (Census of India 2011).

2.2 Field Research observations on the energy situation in rural UP

As argued in the Introduction Chapter, Agricultural Household Model (AHM) is a suitable model to analyze the WEF nexus around the energy decision making process of households. For the analysis with AHM, following 5 sets of information were collected in the household surveys:

- Household demography (Gender, Education, Occupation, Age related information)
- Household income sources (Revenues and Investments (labor & capital) on agriculture-crops, agriculture- livestocks, service, enterprise, business, remittance)
- Household expenditures (food, energy, medical, education)
- Asset endowment of household (land, livestock, farming equipments, energy equipments, credit)
- Household energy use for household thermal energy, lighting energy and agricultural energy (energy types and quantities consumed in different seasons, characteristics of energy conversion technologies used, characteristics of fuel sources, expenditures (labor, capital & operational) on energy use, own produce versus market purchase)
- Household health (disease type and annual expenses)

Before the start of household surveys, an FGD was first organized in each surveyed village. This was carried out to understand the social structure of village for including all the possible social and economic variations in the household surveys, energy resources at the village level (data on forests and the rules to access, livestock resources in the village, cropping patterns and the uses of agricultural residues, power equipments (transformers, government cables, solar street lights) supplied by the government), community based energy initiatives such as instances of solar mini grids, consumption and supply information of local energy markets (irrigation water, bio-energy, commercial fuel).

This section presents the major field research observations on household energy use and the local energy markets. It is to be noted that out of 400 household surveys, data from 380 households is used in the research. This section starts with table 2.4 and table 2.5 below which presents the household energy use patterns for cooking and lighting (& electricity) respectively at both state as well as individual village level. For explaining the energy situation in each surveyed village in UP in section 2.2.2 (making use of table 2.4 and table 2.5), firstly, the fuel characteristics and the reasons for their preferences / non-preferences is described in section 2.2.1. In section 2.2.3, local energy markets in each surveyed village is discussed.

The table 2.4 below presents the percentage of surveyed households using different primary cooking energy fuels in different seasons (village wise). Table 2.4 has the following major depictions, which will be further elaborated in section 2.2.1 and 2.2.2. Firstly, it shows that cattle dung cake is primary cooking fuel for majority of HHs in UP. Secondly, wood is a primary fuel for majority of HHs in Rae Bareilly district whereas crop residues is a primary fuel for majority of HHs in Sant Kabir Nagar District in the winter season. Thirdly, during Monsoon, more number of HHs use LPG as primary fuel. Lastly, Biogas is almost non-existent. Table 2.4 is discussed in detail in section 2.2.2.

Table 2.4: Household thermal energy usage in surveyed villages in different seasons of year

Cooking Fuels	**Percentage of households with primary source of cooking energy in each surveyed village and in the UP (combined)**							
	MG	OK	MP	BM	MH	AY	MM	NV	**UP**
Summers									
Dung Cake	57.6%	58.8%	30.0%	35.7%	25.0%	79.3%	73.2%	90.0%	**58.7%**
Firewood	8.5%	5.9%	60.0%	47.1%	8.3%	1.7%	19.5%	0.0%	**19.7%**
Crop Residue	1.7%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.5%**
LPG	32.2%	31.4%	10.0%	17.1%	66.7%	19.0%	7.3%	10.0%	**20.8%**
Biogas	0%	0%	0%	0%	8.3%	0%	0%	0%	**0.2%**
Winters									
Dung Cake	10.2%	33.3%	35.0%	34.3%	33.3%	77.6%	75.6%	75.0%	**46.8%**
Firewood	1.7%	5.9%	52.5%	50.0%	8.3%	1.7%	17.1%	2.5%	**18.4%**
Crop Residue	55.9%	27.5%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	**13.4%**
LPG	32.2%	31.4%	12.5%	15.7%	58.3%	19.0%	7.3%	12.5%	**20.8%**
Biogas	0%	0%	0%	0%	8.3%	0%	0%	0%	**0.2%**
Monsoon									
Dung Cake	57.6%	60.8%	50.0%	44.3%	16.7%	60.3%	56.1%	75.0%	**56.1%**
Firewood	1.7%	0.0%	32.5%	24.3%	8.3%	1.7%	4.9%	0.0%	**9.2%**
Crop Residue	0.0%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.3%**
LPG	40.7%	35.3%	17.5%	31.4%	75.0%	37.9%	39.0%	25.0%	**34.2%**
Biogas	0%	0%	0%	0%	8.3%	0%	0%	0%	**0.2%**
Source: Author's own field surveys									

The table 2.5 below presents the percentage of surveyed households using different types of lighting energy source (village wise). It has the following major depictions, which will be further elaborated in section 2.2.1 and 2.2.2. Firstly, it shows that kerosene is used by most of the Households for meeting their lighting needs. Secondly, electricity stealing is observed everywhere but most predominantly in MP and MM villages. Thirdly, because of unreliable electricity grid, more HHs (mostly rich) are now opting for battery storage. Lastly, solar is gaining popularity for residential lighting and electrification.

Table 2.5: Lighting and electricity situation in the surveyed villages

Lighting source by households	**Percentage of households with mentioned lighting sources in surveyed villages and in UP combined**								
	MG	**OK**	**MP**	**BM**	**MH**	**AY**	**MM**	**NV**	**UP**
Legal electricity	61.0%	66.7%	35.0%	45.7%	100.0%	63.8%	17.1%	37.5%	**50.3%**
Illegal electricity	8.5%	13.7%	40.0%	11.4%	0.0%	20.7%	70.7%	2.5%	**20.8%**
Absolutely no kerosene	1.7%	0.0%	0.0%	2.9%	66.7%	8.6%	4.9%	7.5%	**5.5%**
Kerosene (primary or secondary)	84.7%	96.1%	97.5%	85.7%	33.3%	84.5%	95.1%	80.0%	**86.1%**
Personal big solar system	10.2%	3.9%	0.0%	7.1%	0.0%	3.4%	0.0%	5.0%	**4.5%**
Solar lantern	3.4%	0.0%	0.0%	2.9%	0.0%	3.4%	0.0%	5.0%	**2.4%**
Battery Banks	16.9%	7.8%	0.0%	2.9%	75.0%	10.3%	9.8%	30.0%	**12.9%**
Rechargeable lamps (Chinese light)	22%	13.7%	2.5%	8.6%	0%	17.2%	36.6%	5%	**14.2%**
Source: Author's own field surveys									

2.2.1 Energy Systems/ fuels used by UP's rural HHs and the reasons for their preference and non-preferences

This section presents the field observations on the preferences and non-preferences of different fuel types/ energy systems for household energy use. Fuels/ energy systems for thermal energy use, lighting & electricity, and irrigation energy are discussed separately in part (a), part (b) and part (c) respectively. Part (d) summarizes the economic and environmental costs of the energy systems which exists in field or have opportunities in the field.

a. Thermal Energy

Cattle Dung Cake as the primary fuel for the majority of HHs: During the field research, dung cake supported by firewood (or crop residues such as mustard stalk) was observed to be the most preferred household cooking fuel. In this combination, the wood or stalk gives initial flame and dung cake keeps the flame long lasting. Figure 2.2 below presents typical traditional bio-energy based cooking practice in UP, as observed in the field. There are several technical and cultural reasons, which makes dung cake a preferred fuel choice and are discussed below. Uttar Pradesh has the largest population of livestock in India and as per India's 19th livestock survey in 2012, livestock population in Uttar Pradesh has increased by 14.01% compared to 18th livestock survey (Ministry of Agriculture 2012). During field surveys, 74% of the households were observed to be having one or more cattle (excl. calves). On the other hand, the forest cover has declined in UP (Times of India, April 2, 2011). During the field research, households also reported dung cake's special heat transfer properties, as it gives useful and constant heat for longer period compared to wood and crop residues which give instant high heat, but their flame dies faster. Therefore, while cooking with cattle dung cakes, unlike with wood and crop residues, household woman (chef) don't need to be continuously present in front of the cookstove, has less exposure to smoke and has more time for other activities. Moreover, households also reported that smoke from dung cake cleans the house from insects and mosquitos. The ash from the dung cake was also being used by few respondents (poor HHs) to clean their utensils and teeth. Another important aspect that favours dung cake is its easy storage, where rural households form a special structure called "Bitora- the house of dung cakes" where cakes can be kept water proof, and this makes it possible to use dung cakes even in the Monsoon time whereas other fuels such as crop residues or wood are difficult to store in monsoon. Another reason for dung cake's popularity is that the dung cakes are majorly produced by household females or female children who don't have much non-agricultural work opportunities because of the social constraints. During the field research, it was observed that on an average, an adult buffalo gives around 22-23 kgs of fresh dung per day while an adult cow gives around 18-19 kgs. After drying, it was observed that the weight of dung cake gets reduced to 1/3rd of the dung cake prepared with fresh dung. Karttek D. 2014 and an interview with local biogas technician in field confirms the above.

Figure 2.2: Field Observation- Traditional bio-energy based cooking in UP
Source: Author’s own field surveys

Firewood: As the wood becomes scarce, there is a growing general trend of using firewood as the supporting fuel along with the dung cakes. With declining forest cover, households were observed to be increasingly using private trees as the firewood source. Van 't Veld et al. 2006 in its study in India identified the similar tendency. Eucalyptus, Poplar, Neem (Azadirachta indica), Babul (Acacia nilotica), Pilkhan (Ficus virens) were observed to be most commonly used tree types for firewood purpose. Here, households were observed to be using thin tree branches for cooking, leaving behind the fat branches intact to be later sold in the market. It was observed that private trees solve several purposes for the households. It serves as natural boundary of the farms and discourage any encroachment by the neighbouring farms. Some households also reported that with trees, it becomes difficult for the neighbours to cut small canals for stealing water from their fields. Privates trees also discourage stray animals from entering the farm and spoiling the crops. Some households claimed that planting such trees spoil crop yields and therefore private trees were more popular amongst large landlords. For the villages which were closer to forests, wood stealing was rampant. In such cases, it was observed that an entire poor household, once in 1-2 weeks, goes out in search of wood and wherever it gets a chance, it cuts big tree branches, be that forest trees or private trees from rich households. Some rich farmers also reported that they caught many small farmers in the process and withheld their axes or even slapped them as a form of punishment.

Crop Residue: Rice, Wheat, Sugarcane, Oil seeds, pulses and potatoes are the chief crops of UP. Table 2.6 presents the characteristics of the residues from these crops which are used for energy or for some other applications.

Table 2.6: Characteristics of crop residues produced in surveyed villages

Crop Residue	Ratio of crop residue to crop fruit (by weight)	Application	Season of use/ harvest
Sugarcane Dry Leaves	0.04	Cooking Fuel	Winters
Sugarcane Green Leaves	0.1	Animal Fodder	Winters
Mustard Stalk	1.8	Cooking Fuel	Summers
Mustard Cake	0.65	Livestock feed	All year
Pigeon pea Stalk	2.5	Cooking Fuel	Summers
Rice Stalk	1.5	Animal Fodder/ Cooking Fuel	Winters
Rice Husk	0.2	Cooking Fuel/ Market Sale	All year
Wheat Stalk	1.5	Animal Fodder	Summers
Source: IISc Bangalore India 2009, Field Experiments and expert interviews with farmers in the field			

Mentioned below are the characteristics of major crop residues from the above-mentioned crops which are used as fuels:

- Sugarcane residues: Sugarcane crop once sowed, gives fruit for 2 consecutive years or may be 3 in some cases. The most common practice of sugarcane harvesting in UP is that poor HHs harvest the sugarcane crop of rich HHs and in return receives free sugarcane green leaves (for livestock feed) and sugarcane dry leaves (for cooking fuel). With 1 hour's labour, a labourer was observed to be getting around 5-7 kgs of dry sugarcane leaves along with around 15 kgs of sugarcane green leaves. In rich districts such as Meerut (village MH), sugarcane leaves are left in field on the first year where it helps in keeping the soil moist whereas in second year it is burnt on field to make space for the next crop sowing. These fuels are only available in Winters as sugarcane is harvested in January (till March). However, they are majorly used by poor HHs as this fuel emits lot of black tar and sparks while burning. Also, it needs constant supervision of women as it gives instantly large heat but gets extinguished soon.
- Mustard stalk, Pigeon pea stalk, Cotton stalk: The same barter trade was observed to be happening for mustard stalk and pigeon pea stalk where poor HHs thrash the crop for free and receives the straw in return. These are used as wood and are majorly used as supporting fuels along with cattle dung cake or used as primary fuels. With 1 hour's labour, a female labourer was observed to be getting around 5 kgs of mustard stalk or 6 kgs of pigeon stalk.

- Rice and Wheat Residues:
    - Rice husk: Rice husk is generally sold to the rice huller who removes the husk from rice in lieu of rice husk. Rice huller then sells the rice husk to local industries or boilers. Rice husk as a fuel, can be used throughout the year because it is convenient to store.
    - Rice and wheat stalk: Wheat straw is a valuable livestock feed and was never observed to be used for fuel. As the wheat straw becomes scarcer (because of declining land endowment and increasing livestock population), rice stalk is increasingly becoming an important livestock feed although the same is acidic in nature, but poor farmers have no choice. However, rice stalk is still used as major cooking fuel in Eastern UP (Sant Kabir Nagar) where cattle endowment is low. It is not used by rich HHs because it produces black tar and sparks while burning. The mass burning of rice stalks was not observed in large scale in the surveyed districts, as farmers in Meerut district mentioned that they are now growing less rice and more sugarcane because of the establishment of new sugar mills in the area. They mentioned that this mass burning is more prominent in the neighbouring districts of Muzaffar Nagar, Bijnor and Sahranpur and that too only in very big farms. Few rich HHs in Eastern UP (Sant Kabir Nagar) district were observed to be burning rice straw on the field because they were using machines for rice harvesting which leave rice straws standing on the field requiring lot of labour for their removal and therefore burining them is a cheaper option.

Bioenergy based cook stoves: During the surveys, bioenergy based traditional cook stoves were observed to be widely used by the households. No household was observed to be using improved bioenergy cookstove. Households reported that they are unaware of such technology. Figure 2.2 above shows a typical traditional cookstove used in rural UP along with its pollution. The details on the emissions emitted is discussed in section 2.2.2.d.

LPG (Liquified Petroleum Gas): It was observed that there exist several cultural perceptions and myths amongst rural communities against LPG. Most respondents reported that the food cooked in LPG gas is not as tasty as compared to the food cooked in dung cake/ wood based traditional cook-stove. Some respondents also reported that cooking in LPG is not good for health. During the FGDs in village MM in the prosperous Mathura district of Western UP, a local Quack mentioned “Eating the food cooked in LPG gas causes acidity and the swelling of the stomach”. In the field research, around 43% of surveyed households had LPG connection but only 20% were using it as primary, and rest were using it for status symbol, or making tea, or cooking emergency food in morning for school going children or cooking fast food. In Monsoon, more number of households were observed to be using LPG as its primary fuel because of the problem of moisture with biomass fuels and difficulty in storing bioenergy during this time. One major factor that stops households from getting an LPG connection was observed to be its high connection costs. As mentioned by respondents, it costs around Rs 4500-Rs 5000 (government rates) to get an LPG connection along with stove and a gas cylinder which they need to refill. Few HHs in Rae Bareilly also mentioned that they had to pay bribe of upto Rs 2000 to get a connection so that they don't have to wait for longer periods.

Biogas: Biogas has been a big failure in Uttar Pradesh. As per government statistics, around half a million family biogas plants have been installed in Uttar Pradesh (Ministry of New and Renewable Energy Website) which were financially supported by several government programs, but most of them are un-operational now. Following are the major reasons that led to the failure of biogas, as told by survey respondents. Firstly, biogas plants were even awarded by government to those households who had less number of livestocks or even just 1 livestock. This may be due to the reason that local government officials had to fulfil some dissemination targets in short span of time and they awarded biogas plants without due diligence. Secondly, many households which earlier used biogas plants mentioned that biogas is a technology failure and they never got sufficient gas for cooking and lighting needs. Some households also mentioned that their biogas plants were installed in shady and cooler areas and therefore didn't work. Many households complained that no technicians (as per the government contract) ever visited to look at the operations of their plants. Thirdly, as more number of families are getting partitioned, the household area is getting reduced. This motivates the household to use the scarce HH land for other useful amenities such as toilets etc rather than biogas plants. Fourthly, there were also misconceptions associated with the slurry produced by biogas plants. Some households mentioned that since gas get extracted from the cattle dung in the biogas plants therefore the slurry coming of the biogas plant is useless. Some households who were aware of the importance of slurry reported that they are fine in handling the cattle dung but slurry from biogas plants being more liquid is very difficult to get transported back to their fields and that is why it is useless. Some household reported that they only needed biogas for lighting and they were never interested in biogas for cooking (taste aspect), however as soon as they got electricity connection, they abandoned it. In the field research, only 1 HH was observed to be using biogas plant. This was an extremely rich and a big landlord with high educational status. To understand the operation of family biogas plants better, a visit was also organized to a neighbouring village in Uttarakhand at the border of North Western Uttar Pradesh, where a household is successfully operating a biogas plant. Figure 2.3 presents an operational biogas plant.

Figure 2.3: Field Observation- Operation of Biogas plant
Source: Author's own field surveys

Electric Cook stoves: In the field research, only few households were observed to be using electric cook stoves (mainly for tea, quick food) but majority of them did not accept that they use these cook stoves because of the following reasons. Firstly, the electric cook stoves available in the villages are filament based, with huge power wattage consumption of 1500 W (but cheap and costs around Rs 300), whereas most of the electric connections of HHs are of maximum 1000 W capacity. This means that such HHs should not use equipment of more than 1000W (combined) and therefore these HHs hid that they use electric cook stoves. Secondly, it was observed that most of the HHs that use these electric cook stoves use illegal electricity connections, so they hid this information. Thirdly, HHs with legal connection fear that their electricity usage may be metered, and they must pay the money while using this energy guzzler. It is to be noted that in some villages such as MG, OK and BM, government has started installing meters in the HHs but none of them are activated. So, HHs are confused if government is recording the energy consumption and that is why they don't use such energy guzzler even if they have them. However, government's initiative of metering the rural HHs, will demotivate HHs from using electric cook stoves.

b. Lighting and Power

Legal Electricity Connection from local electric utility: All the current legal electricity connections as observed in the field research fall in the category of Unmetered Connections where hhs can consume as much energy as available subject to availability of power. However, these unmetered electricity connections are a big problem to the government because of the following reasons: It leads to inefficient use of power as HHs are not motivated to consume power judiciously and it leads to severe losses to power utilities. But since, rural communities are vote banks for the political parties, power utilities are forced to sell power to these unmetered loads. Moreover, in Central and Eastern Districts of UP (Rae Bareilly and Sant Kabir Nagar), households mentioned in the FGDs that many of them don't pay their electricity bills. They also mentioned that there is a tendency of the governments to write off farmer's electricity dues before the state or central elections. However, HHs which are from respectable professions (such as teachers) make it a point to pay the bill on time. Since power is unmetered, there were many cases when a household having a legal electricity connection further shares its connection with his neighbours and shares the monthly bill with them. Since power is unmetered, it is difficult for the electricity authority to assess the points of power thefts. All the above reasons lead to losses to local electric utilities. As a result, they are unable to buy additional power to balance the demand and hence they resort to excessive load shedding. As a result, villages only get power in the night time when it is not needed at all. All the villages reported that during summers the situation is most pathetic, and they get electricity supply after 10 pm till 5 am and then few hours in the day time, so effectively they get around 8 hours of electricity. This too is not fixed and there may be several days when they don't get electricity at all. In winters, situation is slightly better compared to summers (which is a high load season due to cooling requirement). So effectively they get couple of hours of more power compared to summers but still they don't get regular electricity during 6 pm to 10 pm. Interestingly, they mentioned that when elections are nearby, they get comparatively better power supply. Also, during the final exams of school students ie during the month of March, electricity supply is better. Since electricity supply is poor, this demotivates the households to pay their electricity bills.

Illegal Electricity Connections: The practice of illegal electricity connections was observed to be working in 2 ways. Firstly, for the households who have local low voltage (LV) electricity lines passing near their HHs, they throw their own electric wire to that LV line, hook it and steal the electricity (Figure 2.4). Whenever they have information that the local electricity line man is on patrol, they remove it. However, the households which have their houses facing main road of the village are unable to steal electricity in this way, because they are always visible. Also, if electricity line is not near the HH, the same cannot steal it. Such HHs adopt the second option. Here, 2 or more HH take 1 electricity connection at the name of any one of the HH. With the legal electricity connection, electric wire comes to their HH. Then, they further extend these wires to their neighbouring households. All the neighbouring HHs then share the electricity bill. Sharing of fees does not creates any dispute because in villages, electricity bill is not metered and HH must pay a fixed monthly price. The relatives which live in neighbourhoods were observed to be using electricity this way.

Figure 2.4: Field Observation- Electricity thefts
Source: Authors' own field surveys

From the above discussions, it can be argued that the reasons for low HH electrification rate in UP may not be the financial constraints of the households, but the unchecked opportunities for stealing power and poor electricity supply demotivate the households to get an electricity connection. However, government has now started taking good initiatives. It has started installing the power meters at the rural HHs. Under the newly launched Deendayal Jyoti scheme, government is dividing the existing electricity feeder into agricultural and non-agriculture feeder. To avoid indiscriminate usage of agricultural loads, electric utility will now be able to disconnect agricultural feeder without impacting household feeder.

Kerosene: Kerosene was observed to be the major source of lighting for most of the households as even those hhs which have grid connection, use kerosene at times of power outages which are very frequent in the evenings. Another reason that encourage HHs to use kerosene is the fact that government distribute highly subsidized kerosene to all the HHs in rural India @ Rs 17/ litre with a limit of 3 litre/ HH whereas the rate in black/ open market is Rs 40/ litre. The 3 litre/ month of kerosene is sufficient for a small HH to run 5 hours of lantern every night in a month. It was validated during field research with an experiment with a kerosene wick lamp which is majorly used in rural HHs. It was observed that 100 ml kerosene could run the wick lamp for around 10-12 hours.

Battery Backup: Due to the unreliable electricity grid supply, power is not available at the timings when it is required the most. Moreover, there are no fixed timings of the power supply. This motivates rich HHs to buy battery technology in which they store electricity whenever it is available and use the backup whenever they require it. Since battery is an expensive technology, HHs generally keep battery somewhere between 12V 40 Ah till 12 V 300 Ah and use an intermediate inverter to run the electric appliances. This is mainly used to serve lighting and fan load. HHs which have battery were observed to be using CFL bulbs and efficient power equipments.

Chinese Lights (Rechargeable Electric Lamps): These are the small lamps which have a small battery in it which gets charged with electric supply and can later be used for running the lamp. These are cheap products manufactured in China and that is why they are locally famous as Chinese lights. This was mainly popular in the villages which were close to cities or markets. Even the HHs which don't have electricity connection use it and charge it from neighbours' houses with electricity connection. Since the neighbours don't pay any marginal costs for the electricity usage, they don't charge any fees. However, there were concerns on the quality of these products in the market.

Big Solar: Big solar is referred to 2 types of solar systems. One is Solar Home Systems (SHS) which comprise of typically a 50-75 W Solar panel installed on the roof of the HH which is then connected to the SHS battery in the house. The SHS comes with lights and fans which are then powered by this battery. It was also observed that Uttar Pradesh Government has a scheme for landless farmers (Lohiya Awas Yojna) where government builds a house for the them and electrification of those HHs is done by SHS. The second type of big solar system is a large solar panel array connected to existing battery system of HH. Here, typically a 200-300 W solar array is installed at the roof and is then connected to existing battery and power equipment of HH. This is usually done by rich HHs which needs power back up for several power equipments. This is gaining more momentum as solar companies are dumping their defective solar panels to the rural market and rural HHs are getting such panels at a very cheap price.

Solar Lantern: This is like Chinese light but is powered by a small portable solar panel.

Public Solar: In few surveyed villages, village chiefs had utilized village development fund to install solar street lights. However, it was observed that rich HHs had got them installed in their own premises and used all their light. It was only the village MM where HHs share the light of street lights and share the expenses incurred in their maintainance.

Gensets: These were only used by few rich households. For the times when grid electricity is absent for long time, rich hhs use it for running submersible water pump for filling their residential water tanks. They also used it in emergency in case of visit of important relatives.

c. Irrigation

In the surveys, Electric tube wells and diesel engines were observed to be the popular water pumping technologies used by households for farm irrigation. There was a great interest on solar water pumps amongst households.

Boring Well: For any of the water pumping technology, boring well is the prerequisite. The depth of boring was observed to be ranging between 100 feet and 300 feet deep with Mathura and Rae Bareilly having shallow ground water tables whereas SK Nagar had the deepest water table. The digging costs of boring well was observed to Rs 120/ feet which also includes the cost of inserted metal pipe and suction pipe.

Diesel Engines: In diesel engine-based pumping, the suction pipe of boring well is connected to the diesel engine. When the engine runs, it oscillates the suction pipe and the water is sucked out. During the surveys, more number of HHs were observed to be using diesel irrigation pumps in comparison to electric tube wells. The reasons are explained in next section. Farms with own diesel engines serve their needs as well as sell water to their immediate farm neighbours at the costs discussed in section 2.4. The figure 2.5 below shows a farm selling irrigation water (from its diesel water pump) to the adjacent farm.

Figure 2.5: Field Observation-Diesel based water pump selling irrigation water
Source: Author's own field surveys

Electric Tube wells: For this technology, first electricity connection is taken from the government electricity distribution company and then the electricity supply is connected to the motor which is connected to the boring well through a pulley. The electricity runs motor which oscillates pulley, and which sucks the water from the boring well. It is to be noted that for agriculture purposes submersible motors are not used. The government fees of getting the electricity connection for tube well costs around Rs 16000 as reported by HHs however, it involves heavy bribes. These bribes were observed to varying between Rs 50,000 to Rs 100,000 across the surveyed villages. The farmers with tube well connections only need to pay a fixed monthly price and they can use the tube well as much as they want subject to the availability of power. Also, these farmers were observed to be selling water to the neighbouring farms at prices which were comparatively cheaper price than that from diesel pumps. This leads to excessive consumption of ground water. The electricity company's officials know this and that's why charge huge bribes for giving the connection.

Solar Powered Irrigation tube wells

During field surveys, no surveyed household/ farm was observed to be using solar water pump for irrigation, however, great efforts were made to identify any such installation in other villages. Finally, one such system was found in village Baraula in Sant Kabir Nagar District that was installed in year 2014. Figure 2.6 below shows the solar water pump. This system makes use of solar PV of around 1800W capacity and a 2 HP DC centrifugal pump. The pump made use of boring of around 100 feet. The entire system costed Rs 2,75,000 and the owner had to pay only 25% of this cost which was around Rs 70,000. This household had male and female members with high education (graduation), comparatively large land endowment of around 4.5 acres, and cultivated vegetables which need regular supply of water but is highly profitable.

Figure 2.6: Field Observation-Solar Water Pump usage in a village in UP
Source: Author's own field surveys

<u>Transportation of water sold</u>

The water sold by pump owners was even observed to be transported till 500 m distance and this was done with pipes whose daily rent was observed to Rs 20 per 100 feet of the pipe.

d. Economic and environmental costs of the available energy systems in rural India

This subsection provides the economic costs (capital costs, fuel costs and operational costs), characteristics (efficiencies, lifetime, system degradation rates) and environment costs (Total Suspended Particle, Carbon dioxide and Carbon monoxide emissions) of different types of energy technologies which are used in villages or have the potential in the surveyed region. This utilizes the literature survey, field research observations, interviews with decentralized energy technology experts from TERI (The Energy and Resources Institute) and local energy system technicians in the field.

While, Appendix Table A1.1 presents the above information on power systems (Solar PV, Battery Backup, Diesel power, Central Grid connection, Biomass Gasifier systems, Biogas Power), Appendix Table A1.2 presents the same on cooking energy systems (Dung, Wood and Crop Residue based traditional as well as improved cook stoves, LPG based cooking systems, Biogas based cooking system), Appendix Table A1.3 covers lighting systems (Kerosene Light, Solar light with and without battery, Central grid based light with and without battery, Diesel Genset based light, Biogas mantle and Gasifier based light) and Appendix Table A1.4 deals in the irrigation systems (Solar Water Pump, Diesel Pump, Biogas based pump, Biomass gasifier based pump, centralized Electricity based tubewell).

2.2.2 Energy situation in the surveyed villages of UP

This section discusses the energy situation in each of the surveyed village. Before explaining the energy situation in each village, it is important to understand the village characteristics. The table 2.7 below presents the characteristics of each surveyed village including its location, agricultural characteristics, proximity to forests and non-agricultural work opportunities.

Table 2.7: General characteristics of surveyed villages

Village characteristics	Surveyed villages							
	MG	OK	MP	BM	AY	MM	MH	NV
Dist. - District HQ (kms)	8	3	11	9	13	22	18	14
Dist. - Market (kms)	7	3	11	9	5	10	1	3
Avg. farm size (acres)	1.42	0.7	1.57	2.47	1.47	2.19	6.23	1.51
Major Crops	Rice, Wheat, Sugarcane (sugar), Pulses, Oil seeds	Rice, Wheat, Sugar, Pulses, Oil seed	Rice, Wheat	Rice, Wheat	Wheat, Millet, vegetable	Wheat, Millet, vegetable	Sugar, Wheat, Rice	Rice, Wheat, Sugar, Millet
Livestock per HH [Nos]	0.79	0.82	1.45	1.87	1.7	1.9	2.9	1.5
Private trees per HH (nos)	3.63	0.71	26.25	56.1	5.2	4.5	3.2	35.73
Proximity to forests (yes/no)	No	No	No	Yes	No	Yes	No	No
Non-Agricultural male labor (# days/hh/ year)	265.2	364.7	243	341	133.83	137.89	236.21	280.7

Village characteristics	Surveyed villages							
	MG	OK	MP	BM	AY	MM	MH	NV
Regular Non-agricultural male labor(days/hh/ year)	170	155.2	128	273.2	111.7	127.4	227.9	236.5
Caste -village chief	Upper	Lower	Lower	Lower	Lower	Upper	Upper	Lower
Dist- Gas agency (kms)	1	3	10	6	8	10	1	4
Below Poverty Line HHs (%)	61.0	21.6	77.5	57.1	8.3	34.5	41.5	17.5

Source: Author's own field surveys
 # regular and irregular
**Note: Average no. of working males per HH as observed in my surveys in UP is 2.2 (males between 15 years to 59 years)*

The above table show that villages differ in terms of distance from the district centre, agriculture systems and opportunities of non-agricultural labour and proximity to forests. Referring to table 2.4 and 2.5, presented below is the energy situation in each surveyed village, as observed during the field research.

I. Village MG

Thermal Energy: This village comprises of majority of small landholder households (poor households). In summers, dung cake is the primary cooking fuel in the village. There are 66% of HHs in this village that have either 1 or more cattle with them (excl. calves). The HHs who don't have cattle either collect dung lying on the grazing lands or get it from the rich households in lieu of labour. Wood is majorly used as supporting fuel with the dung cakes. HHs which have private trees (rich HHs) trim the trees for firewood. Women and children of poor HHs that do not have private trees, collect dry tree branches/ mango leaves from the private trees or government trees and this sometimes leads to disputes. HHs which don't have wood use agricultural residues such as Mustard stalk or pigeon pea stalk as supporting fuels. Poor HHs (agricultural labourers) receive free agricultural residues from rich hhs in lieu of thrashing of their mustard and pigeon pea crops. The HHs that are rich and primarily dependent on non-agricultural work, have completely switched to LPG. This village is benefitted by the proximity to the gas agency. Now, even poor HHs who have scarcity of above discussed bioenergy are shifting to LPG now, although not as primary fuel but use it at the time of fuel scarcity. In winters, crop residues such as sugarcane leaves and rice straw become the primary cooking fuel for majority of households in the village. This fuel is primarily used by the poor HHs (agricultural labourers) who receive free sugarcane green leaves and sugarcane dry leaves in lieu of the harvesting of sugarcane crop of rich households. The HHs that grow their own rice, use a part of it as livestock feed. Rich HHs never use rice stalk as fuel. Rich households harvest their rice crop by machines and this process leaves residues scattered in the farm and some residues keep standing on the field. A part of these residues is collected by poor households and remaining is burnt by rich households on the field. Since crop residues are majorly used as primary fuel in winters, cattle dung produced during such time by HHs is stored for the Monsoon season. In monsoon, more number of HHs use LPG as primary fuel because of the scarcity of wood, cattle dung cake and crop residues. There are also few HHs that are unable to meet the fuel requirements and at some point of time, they have to buy dung cakes from the cattle rich HHs There are around 35% of HHs that even do cash purchase of biomass fuels in times of scarcity of biomass.

Lighting and Electricity: As shown in table 2.5, 61% of HHs in this village mentioned that they have legal electricity connection whereas another 10% mentioned that they use illegal electricity connection. The reason for this high percentage of legal electricity connection is the high percentage of BPL households (with Below Poverty Line card) in this village that received free electricity connections from the government in the past. The other important reason, as observed in the FGD, is that under the backing of local strong upper caste Hindu HHs, very few HHs in the village pay their monthly electricity bills to the government. HHs also mentioned that before the elections there is a tendency that government writes off their electricity bills. This motivated many HHs to get a free BPL electricity connection as they don't pay electricity bill anyway. Kerosene was observed to be used by most of the HHs, in case of power outage. Solar systems and batteries were used by rich HHs whereas Chinese lights were used by poorer HHs as backup systems. This village has more than 15% of HHs with big solar systems and large battery backup system and this was common amongst HHs involved with regular non-agricultural work who have greater access to market and have regular income and are close to district centre.

II. Village OK

Thermal Energy: This village falls in the same district as MG and shows similar characteristics. However, being close to the district headquarter, most of its HHs are involved in non-agricultural work (regular and irregular) and have sold part of their land to the builders and that is why agricultural production and therefore agricultural residues production is low. Being close to the city, milk sale is still a good business for the HHs that have high yielding cattle. This makes cattle dung cake a major fuel in all the seasons. The number of private trees per HH is very low. Here, more number of HHs (around 47%) do cash purchase of biomass fuels in times of scarcity as they divert much of their time on non-farm employment as their time has greater value and they have more cash to pay. This was the only village where HHs pay direct cash to the rice hullers but don't sell their husk to the rice hullers and use rice husk as supporting fuels with dung cakes whereas in all other villages HHs sells husk to rice huller in lieu of free dehusking. Since HHs spend more cash on direct purchase of bioenergy, have more involvement in non-agricultural employment, more and more number of HHs are switching to LPG as primary fuel now that is easily available in nearby gas agency

Lighting and Electricity: It has similar features as of MG, however, compared to village MG, it has less number of HHs with personal solar and battery. The reason could be that in village OK, although more HHs are associated with non-agricultural labour, yet most of them are associated with irregular labour jobs. For instance, in village MG average non-agricultural male labour days per HH is 265 days out of which 170 days are used in regular jobs and 95 days in irregular labour jobs. In OK, average non-agricultural male labour days per HH is 365 days out of which 209 days are used in irregular labour jobs. These irregular jobs include loader in shops, coolie in railway station, and labourer in factories. It is to be noted that in UP average number of working males per HH is 2.2.

III. Village MP

Thermal energy: Firewood is primary fuel for village's HHs throughout the year except in Monsoon when HHs use their stored cattle dung cakes for cooking. Rich farmers have lot of private trees as there are lot of waste lands in the vicinity in which they plant their own trees as a way of claiming waste lands. Poor HHs collect wood from waste lands which have woody shrubs or cut dry branches from the private trees of rich farmers. However, several poor households reported that whenever they get chance they steal the comparatively big logs of wood from the private trees of rich farmers, so that they can save time. This is usually done by households which have more young men in the family as they are stronger and quicker. Other HHs collect wood from the waste lands when they go to graze their animals or when they go to fields for toilet. Some rich farmers reported stealing of wood by poor HHs. Sometimes they ignore and at times they withhold their axes. This village has the least number of HHs with LPG connections as it is very remotely located from district headquarters and any nearby big market and gas agency is very far off. Non-agricultural work opportunities for HH is limited because of the distance from market and most of the HHs are dependent on agriculture. Non-agricultural work opportunities include laborers in Brick Kilns, government MNREGA jobs in which government assures 100 days of work per HH per year (building canals, roads etc) but wage per day is only Rs 150/ day. In Monsoon more number of HHs start using LPG as primary fuel because wood is moist and waste lands are water logged. There is no HH that use crop residue as primary fuel. Rice and wheat are the major crops of this village and the wheat straw and rice straw are only used as livestock feed as this village has greater endowment of livestock per HH and moreover wood is in plenty now.

Lighting and Electricity: This village has more number of HHs using illegal electricity connections. This is because it is a remotely located village and therefore has lesser patrolling by electricity inspectors. There is no personal solar system in the village. But the village chief with his village development fund has installed 5 solar street lights in the village. It was observed in the survey that the rich HHs had got them installed within their own premises for their own use. Modern electricity systems such as personal solar, battery backup systems and even cheap Chinese lights are absent from the village.

IV. Village BM

Thermal Energy: This village has similar characteristics as MP, however LPG usage is comparatively higher then village MP because it is comparatively closer to District Headquarter/ market and has lot of NGO activities. This village has a forest in its vicinity which has turned into a waste land with only woody shrubs and few trees. As told by HHs in the FGD, there is a rule for accessing forest, but it is never respected. As per the rule, trees in forest cannot be cut and if somebody is caught, then the village chief reports it to the lekhpal (local government official). Thereafter as per rule 15C of local government, defaulter could be asked to pay some penalty. However, village chief never takes it seriously and never informs it to the Lekhpal because he fears losing the vote bank from the family/ clan whose member has been caught. Because of this, wood stealing is rampant. Not only do these HHs steal wood for HH thermal energy needs but also sell it in market. So, now the forest has turned into a degraded forest. Now rich and big landlords have grown lot of private trees around the boundary of farms or in the waste lands close to their farms with the intention to claim waste lands later. Poor HHs steal the wood from these trees for their cooking needs. This stealing is done by whole family that goes out early morning and steals the wood whenever the opportunity exists (private trees or few remaining trees in forest). Rich farmers expressed the same concern in the FGD. The hhs which have small children or whose members are not strong, goes to the forest in search of wood from woody shrubs which takes time. On an average, a household spent around 470 hours a year in the collection of HH Energy for cooking in this village.

Lighting and Electricity: The parent district of this village is Rae Bareilly and is the parliament constituency of Mrs Sonia Gandhi, the president of Indian National Congress. Mrs Gandhi has her guest house in this village and therefore there are a lot of developmental activities in the village such as solar power projects. This village has more legal electricity connections although the legal or illegal status cannot be confirmed, and it is suspected that few of the HHs who claim legal electricity connection status might be having illegal connection. For the 10% of HHs which have personal solar systems, the same have been donated by an NGO. Explained below are the NGO supported solar power projects in the village.

Solar Lantern Charging Station in village BM

TERI (The Energy and Resources Institute) has set up a solar lantern charging station in the village in year 2012 with 100% grant. The solar power plant (around 300W solar) charges 50 lanterns at a time (figure 2.7). The operator of this charging station rents these lanterns to the local villagers on a daily fee. The part of the revenue generated is spent on the after-sales service support of the charging station and the remaining is pocketed by the operator. This mechanism ensures the sustainability of the charging station. The operator has now stopped renting out these lanterns to the village HHs because some of them don't pay the rent regularly and misuse the lanterns i.e. make them dirty or overuse them. He has now started renting these lanterns only to the local shops at the rent of Rs 5/ night. He mentioned that around 50% of the lanterns are rented whereas remaining lanterns are faulty. Despite several complaints to TERI, fault rectification has not taken place.

Solar drinking water pump in village BM

With the sponsorship of a local Bank, 3 solar drinking water pumps have been installed at 3 locations in this village. This was done in year 2015. Here a 500W solar plant is set up which powers a water pump to pump ground water and store it in the overhead 5000-liter tank. This tank is then connected to cluster of around 30-40 HHs who get round the clock supply of water. Local communities only provided around 20 m^2 land for the plant whereas all the capital cost was borne by the Bank. There is an understanding amongst HHs that they bear the operation & maintenance costs themselves.

Figure 2.7: Field Observation- Solar Lantern Charging Station in village BM, UP
Source: Author's own field surveys

V. Village Mohammadpur Hayak

Thermal Energy: This village is very prosperous comprising of big landlords. It is very close to a market. Here, agricultural labourers are migrant workers from the province of Bihar who lives away from village. LPG is the primary cooking fuel for most of the households and 1 HH was also found to be using biogas. This HH has been using biogas for the last 20 years and is very satisfied. This high proportion of modern cooking energy could be attributed to high income, non-agricultural work among HHs and presence of gas agency next to the village. Middle age people do agriculture, but all the youths are involved in non-agriculture work such as truck business, construction etc. Few agricultural labourers in the village use cattle dung cakes along with wood from the private trees around the village. Sugarcane is grown extensively but the residues are burnt on field as there are no takers for residues or are spread on the field so that they can retain moisture in the field.

Lighting and Electricity: In this village every HH has a legal electricity connection and almost every household has a battery or diesel genset as the power back up system. 5 solar streel lights were installed by the local government however only 2 are properly working and the battery of 1 solar street light has been stolen. There was no initiative by communities to repair the broken street light as every HH has its own power back up system.

VI. Village AY

Thermal Energy: This village falls in one of the most prosperous districts of Uttar Pradesh. It is majorly inhabited by Bhagels, cattle owning caste, so village has a large livestock population. Around 73% of the HHs have 1 cattle or more. Cattle dung cake is the primary fuel of most of the HHs throughout the year. Wood is very scarce and average landholding is only around 1.5 acres. Wheat, potato and millet are the major crops in the village. The residues from wheat and millet is only fed to the livestock. HHs use crop residues such as cotton stalk or pigeon pea stalk (from neighbouring village) as the secondary fuel along with dung cake. The neighbouring village grows different varieties of crops, thanks to the government canal that has come till that village. Around 38% of the HHs in this village reported cash purchase of the fuels at some point of time. Although LPG connection is owned by around 55% of the HHs, only 20% use it as a primary fuel as cattle dung is widely available. LPG consumption increases in Monsoon.

Lighting and Electricity: This village has high electrification rate. Number of HHs with modern electricity systems such as solar and battery is small, because it is very far from the main city and most of its HHs are involved only in the agricultural activities. The village has 8 solar street lights which have been installed recently. 4 Years ago, there was a solar drinking water pump installed in the village however it has turned into a ruin. HHs reported that since everybody in the village has a hand pump, nobody bothered about the maintenance of solar drinking water pump. It was also reported that local HHs themselves stole wiring of the water pump.

VII. Village MM

Thermal Energy: It is a remote village on the banks of river Yamuna. It has a community forest of around 85 hectares which has been given to forest department. HHs in this village have high livestock endowment. Number of private tress per HH is less. Cattle dung cake is the primary fuel throughout the year and wood is used as the supporting fuel. Rich HHs take wood from their own private trees and poor HHs collect wood from the forest. Here, stealing of wood from the community forest is widespread. HHs having their farms near the forest's boundary cut forest trees during their crop's harvesting and hide them in their agricultural produce in tractors and bring them to the houses. HHs which have strong young men steal wood from the forest few times in a month in the wee hours of the day. The remaining HHs (who can't steal) send their women to collect twigs from the forest in the day time and as forest guards are present in the day time, stealing of big wood blocks becomes difficult for them. The average amount of time spent per HH in the cooking fuel collection is around 503 hours per year. The village is inhabited majorly by upper caste Hindus and many of them have LPG connection as a status symbol (55% of the surveyed HHs had LPG connection), however only 7% HHs used LPG as primary cooking fuel. LPG consumption increases in Monsoon.

Lighting and Electricity: This village is an officially un-electrified village and the electricity line available in the village is only for the agricultural water pumps which are installed at a distance from HH clusters. However, around 15% of HHs have taken legal electricity connection from agriculture pumps although they had to bear the cost of long wiring. This electricity line has been hooked by several HHs who have taken illegal electricity connections. Since this village is far from district HQ, there is less patrolling from the electricity inspectors and therefore electricity stealing is rampant. Because of mass stealing of power, power supply voltage is extremely poor. Further, since this village is an un-electrified village, local government has installed 10 solar street lights across the village. Since this village is made up of 70% Brahmins there is a lot of unity among HHs, so they collectively maintain the solar street lights. As observed in surveys, there were instances when streel light broke down and HHs collectively fixed it and shared the expenses. Several HHs in this village use Chinese rechargeable lamps because this village is close to a Hindu pilgrimage site having lots of markets from where local youths purchase new and cheap lighting products.

VIII. Village NV

Thermal Energy: Cattle dung cake is a primary fuel in all the seasons. Here HHs have the tendency to grow private trees around the farm which gives wood as a supporting fuel with the dung cake. With its proximity to the main market, the gas agency is close to the village and therefore around 43% of the HHs have LPG connection but majority of hhs use LPG only as a secondary fuel because of the taste considerations. In winter, some poor HHs start using crop residues such as dry sugarcane leaves which they get in exchange to harvesting of sugarcanes.

Lighting and Electricity: This village has medium electrification rate. This village has only 17% HHs that have BPL (Below Poverty Line Cards). Battery storage and Personal Solar is becoming very popular in this village as this is close to a large market and HHs have more choices and negotiating power to procure modern lighting/ electricity technologies. Since it is a large village close to an important market and industrial area, this village has got prominence and plays active role in local politics. Therefore, it has been awarded around 20 Solar street lights.

2.2.3 Local energy markets in the surveyed villages of UP

This section presents the major characteristics of the irrigation water markets, bio-energy markets and the fossil fuel markets in the surveyed villages.

a. Irrigation water markets

The table 2.8 below presents the characteristics of water markets in surveyed villages. The major depictions are as follows. There are no or insufficient government water pumps in the surveyed villages. Farms with personal irrigation water pumps sells water to neighbouring farms with no personal irrigation pumps, and this forms the water market in the village. Farms with electricity tubewells sell water at cheaper rate compared to that with diesel pumps because of their zero marginal operational costs. Water markets in Eastern UP villages (MG, OK, MP, BM) are more prominent where there are more water buyers than sellers. Since these villages have lesser number of electric tube wells, water buyers in these villages pay substantially higher prices compared to those in Western UP villages. In village NV which has a large cluster of Muslim population, there was a tendency of sharing water pumping facilities. One reason behind this could be that Muslims have bigger families and each HH is somehow related to each other. Village MM also had similar sharing tendency because 70% of the village was from Brahmin community.

Table 2.8: Irrigation water markets in surveyed villages

Characteristics of water markets in surveyed villages	Surveyed Villages							
	MG	OK	MP	BM	AY	MM	MH	NV
Number of HHs (Nos)	224	182	163	242	355	129	50	303
Number of government electric Tube wells (Nos)	1	0	0	0	0	0	0	1
HHs surveyed (Nos)	59	51	40	70	56	41	12	41
Average HH landholding (acres)	1.42	0.7	1.57	2.47	1.4	2.2	6.2	1.5
HHs with own electric tubewells (%)	2	8	13	1	13	22	67	7
HHs with own diesel pumps (%)	32	16	20	44	11	34	8	39
HHs dependent on water purchase (%)	63	76	68	54	77	44	25	49
Water price -Diesel pump (Rs/ hr)	150	150	150	150	150	120	0	150
Water price-Electric tubewell (Rs/hr)	100	100	60	100	90	80	30	100
Water sale/ diesel pump (hrs / year)	53.5	30	33.2	21.8	18	15	0	20
Water sale/ tubewell (hrs / year)	80	85	80	20	221	150	165	80
Source: Author's own field surveys								

b. Bio-energy markets

Table 2.9 presents the crop residue, cattle dung cakes and wood markets in each village. Here, mostly households are the buyers and sellers of the energy commodities.

Table 2.9: Bio-energy markets in surveyed villages

Characteristics of bio-energy markets in surveyed villages	Villages							
	MG	OK	MP	BM	MH	AY	MM	NV
HHs surveyed in village (Nos)	59	51	40	70	12	58	41	40
Crop Residue Market								
Expense on crop residues per surveyed hh (Rs/ year)	5	57	0	0	0	359	0	3
Sugarcane dry leaves sold per surveyed hh (kg/year)	254	110	0	0	0	0	0	459
Price-Sugarcane dry leaves (kg /labor hour)	4-6	4-6	n/a	n/a	0	n/a	n/a	4-6
Mustard straw sold per surveyed hh (kg/ year)	35	4	0	4	45	0	0	14
Pigeon Pea straw sold per surveyed hh (kg/ year)	8	5	0	0	0	0	0	0
Price-Mustard/ pea straw (kg /labor hour)	4-5	4-5	n/a	4-5	4-5	n/a	n/a	4-5
Rice husk sold per surveyed hh (kg/ year)	258	45	219	237	70	7	0	108

Characteristics of bio-energy markets in surveyed villages	Villages							
	MG	OK	MP	BM	MH	AY	MM	NV
Price - Rice Husk (Rs/kg)	2-2.5							
Price - Rice Straw (Rs/kg)	1-1.5 (depending on season)							
Price – Wheat Straw (Rs/kg)	4-5.5 (depending on season)							
Dung Cake Market								
Livestock per HH (Nos/ HH)	0.79	0.82	1.45	1.87	2.91	1.74	1.92	1.48
Dung cake sellers in village (Nos)	8	13	5	2	0	13	4	6
Dung cakes purchased by surveyed hh (kg/year)	57	90	10	0	0	265	36	405
Price-dung cake (Rs/ kg)	5-7	5-7	4-5	4-5	0	1.5-2	1.5-2	1.5-2
Firewood Market								
Private trees/ HH (Nos)	3.67	0.7	26.2	56.1	3.2	5.2	4.8	35.7
Sellers of wood in village (Nos)	0	1	5	13	2	1	0	5
Firewood purchased per surveyed HH (kg/year)	70	123	143	82	0	18	0	87
Firewood price (Rs/ kg)	7	7	5	5	6	6	-	6
Source: Author's own field surveys								

Crop Residue market: The crop residue markets are more prominent in Eastern UP (village MG and OK) where large landlords are the sellers of crop residues and small landholders/ agricultural labourers are the buyers. The crop residue trade in these villages happen through barter trade whereas crop residue market in village AY is based on cash purchase. Sugarcane leaves, Mustard stalk and Pigeon pea stalk are generally traded through barter trade where poor HHs go to farms of rich farmers and harvest/ thrash crops in lieu of the residues. In case of sugarcane, for each one hour of labour, the labourer gets around 4-7 kgs of dry leaves along with 10-15 kg of sugarcane top or green leaves. For mustard/ pea straw, a labourer receives 15-20 kg of mustard or pigeon pea stalk in 4-5 hours of labour. For other crop residues (rice straw and wheat straw), they are generally sold by hhs in cash price, whereas rice husks are purchased by rice hullers in lieu of free dehusking, which further sell husk at the rate of Rs 2.5/ kg.

Dung cakes market: These markets are most prominent in Village AY and village NV (both in Western UP) as both have significant cattle herder community (Bhagel and Pal community respectively). In Eastern UP (village MG and OK), supply is less, and demand is more and therefore selling price of dung cake is high whereas it is opposite in Western UP villages such as AY and NV.

Firewood market: Households with private trees were observed to be selling wood logs to the local traders who further sell them to the big market. The wood logs which are thin and shapeless are sold by local traders to the local HHs at around Rs 5-7 per kg depending on the village. There also exists barter trade between HHs for wood, where poor HHs cut the wood logs for free for the rich HHs and take the discarded thin branches in lieu of labour. However, this barter trade is not included in table 2.9. Village MP, BM and NV have the highest number of HHs selling wood from the trees because they have high number of private trees per HH. Village MP and BM also have significant number of HHs purchasing wood from market, however it is suspected that such households were lying and were shielding their wood thefts. Village MG and OK have lot of wood buyers because it has little number of private trees and lack any forests in the vicinity. Firewood price is similar for all the villages except village MP and BM where it is little cheaper as these villages/ regions have lot of waste lands in the surrounding.

c. Fossil fuel markets

The table 2.10 below presents the market of kerosene, LPG and diesel fuel in/ near the surveyed HHs. It also distinguishes between the government's PDS (public distribution shops) and open market sale of these fossil fuels.

Table 2.10: Fossil fuel markets in surveyed villages

Characteristics of fossil fuel markets in surveyed villages	**Villages**							
	MG	OK	MP	BM	MH	AY	MM	NV
No. of HHs surveyed in village	59	51	40	70	12	58	41	40
Kerosene Market								
PDS Kerosene price (Rs/ l)	19	19	17	17	17	17	17	17
Distance from PDS shop (km)	3	1	0	0	2	6	0	0
Open market Kerosene price (Rs/ l)	40	40	35	35	35	30	35	40
LPG Market								
PDS LPG price (Rs/ltr)	33	33	33	33	33	33	33	33
Distance from PDS shop (km)	1	3	10	6	1	8	10	4
Open market LPG price (Rs/ l)	80	80	80	80	80	100	100	100
Diesel Market								
Diesel price (May 2015)	50	50	50	50	50	50	50	50
Distance from Diesel Station	1.5	2	1.5	0	1.5	5	2	1.5
Source: Author's own field surveys								

It shows that there is a significant cost difference between the prices of kerosene and LPG in PDS shops and the open market, where the former sells the commodities in significantly lesser prices (highly subsidized by the government), however former has constraints on the monthly allocation of these resources per HH, for instance only 3liter kerosene per hh per month can be provided through PDS shops. However, few HHs complained that some influential HHs even get 3 to 4 ltrs/ month which they use for running water pumps and there were frequent disputes on this. It was observed that hhs purchased kerosene from open market only in case of emergency as 2.5-3 ltr/ month of kerosene was found to be sufficient to fulfil the minimum lighting demand of HHs. The LPG PDS market is more streamlined with a fixed quota for each HHs, however here the major challenge for any hh is to get the LPG connection which needs initial money investment. Also, refuelling of cylinders costs time and extra money as discussed in section 2.1. In open market, LPG costs double price and hhs only use it in case of emergency. Diesel market was streamlined and almost all the surveyed villages have proximity to diesel outlets from state owned oil companies such as IOCL (Indian Oil Corporation).

2.3 Comparison of the field surveys and the government energy surveys of year 2011

Household thermal energy use: Field Research observations show that cattle dung cake is the major cooking fuel in rural Uttar Pradesh with around 53% of surveyed HHs using it as primary cooking fuel in year 2015 whereas NSSO 2015 showed that around 33.4% HHs in UP were using cattle dung cake as primary fuel in year 2011-2012. Further, field research observations show that around 20% of rural HHs were using LPG as primary fuel in year 2015 whereas NSSO 2015 showed that around 7% of rural HHs were using LPG as primary fuel in year 2011-2012. Comparing NSSO and field research data, both appears to be in sync with each other. The trends from NSSO 2009-2010 to NSSO 2011-2012 suggests that rural HHs using cattle dung cake as primary fuel in India has increased by around 52% in 2 years whereas percentage of rural HHs using firewood as primary cooking fuel has decreased by 11.8% in 2 years (NSSO 2015, page number 16). Further as discussed earlier, livestock population in Uttar Pradesh is on increase where between year 2007 and 2012, livestock population increased by 14%. Similarly, trends between 2009-2010 and 2011-2012 of NSSO, shows that there has been an increase of 35% in the number of HHs using LPG as primary (ibid). With regards to quantities of bioenergy consumed by HHs, NSSO 2014 presents the per capita fuel wood consumption for cooking in rural UP to be around 11.8 kgs/ month. Considering average HHs size of 6.8 from surveys, the average yearly firewood consumption per HH comes out to be around 962 kg/ HH/ year. Whereas the field research gives this value to be around 874 kg/ HH/ year. Considering the above discussed argument of decline in percentage of HHs consuming firewood as primary cooking fuel, field research value looks in sync with NSSO data. Moreover, while recording the firewood consumption per month, NSS 2015 might have failed to capture the seasonal variation in the firewood consumption. Else then firewood, NSS did not capture the direct quantities of cattle dung cakes and crop residues consumed by HHs. However, the same report suggests that monetary value of per capita per month consumption of dung cake to be Rs 27.28, which translates to Rs 2203 per HH per year. Considering the value of dung cake to be Rs 1.5 to Rs 1.7/ kg in Western UP (which has more dependence on dung cake) 5 years ago, this translates to 1.3- 1.5 tonnes of dung cake per HH per year. Field research observed average yearly consumption of dung cake and crop residues was 1.7 tonnes and 0.16 tonnes per HH per year respectively. With the above discussions, it can be concluded that field research results are in sync with the trend of government surveys.

Household Electrification: The NSSO 2011-2012 data showed rural HH electrification in Uttar Pradesh to be around 40.4%, whereas, field research observed it to be around 50% (HHs using legal electricity connection). It is to be noted that within this legal electricity connection category, there exists households which have legal connection but never pay the bill or the HHs which have never received any bill. Moreover, in the field research, it was observed that there were additional 20% HHs, that mentioned that they are using illegal electricity connection. It is suspected that government household surveys would have been unable to capture these illegal electricity connections because HHs would have denied their illegal electricity status in front of Government Census staff. With regards to kerosene consumption for lighting, NSS 2014 gives the monthly consumption to be 3.36 ltr/ month/ HH, whereas field research gave the average HH monthly kerosene consumption to be 2.81 ltr/ month. This slight difference may be because in NSS surveys, they might have failed to capture the fact that HHs also use some percentage of their kerosene for igniting the traditional bioenergy in the cookstove, whereas this field research figure is solely for lighting purposes.

2.4 Field observations: Household's energy utilization and its linkages with WEF Nexus

This section presents the field research observations on the linkages between household energy utilization and its food security.

a) Modern energy utilization and the household livelihoods

The following table 2.11 shows that the household which used traditional bio-energy as primary cooking energy spent on an average around 491 hours per year on the energy collection, whereas, household that used LPG as primary cooking energy spent on an average only 115 hours per year on the energy collection. This saving in time can be used for productive activities. For instance, during the field research, a household female in village LL was observed to be producing Bidis (Cigarettes) and was receiving income @ Rs 15/ hour of labour. There were other similar instances of household females sewing blouses of other women @ Rs50/ blouse/ 4-6 hours of labour.

Table 2.11: Annual household time on energy collection by different household types

HH characteristics	Annual time on energy collection			
	female (hours/ year)	male (hours/ year)	child (hours/ year)	Total HH (hours/ year)
HHs with traditional biomass as primary cooking fuel	361	42	88	491
HHs with LPG as primary cooking fuel	90	9	17	115
Author's own household surveys				

b) <u>Modern energy utilization and the diversion of cattle dung to farms for fertilizer use</u>

Table 2.12 below presents the field observations that households using LPG as their primary cooking fuel, diverted on average 51% of their annual cattle dung to their farms whereas households that used traditional biomass as primary cooking fuel were only able to divert 23% of their cattle dung to farms.

Table 2.12: Household's utilization of dung for cooking and farm manure by different household types

HH characteristics	Percentage of produced dung spent by HH on:	
	cooking fuel	farm manure
HHs with traditional biomass as primary cooking fuel	44%	23%
HHs with LPG as primary cooking fuel	23%	51%
Author's own household surveys		

Further, table 2.13 below shows that the HHs which used LPG as a cooking fuel (and who allocate more dung to their fields than cooking) had higher crop yields compared to HHs which uses traditional biomass as cooking fuel. This is particularly significant for potato crop which is highly sensitive to manure inputs as told by respondents. One of the reasons may be that these HHs divert most of their dung to their farms.

Table 2.13: Crop yields of surveyed HHs that use LPG viz-a-viz that don't use LPG as cooking fuel

HH characteristics	Crop output (Kgs/ acre)			
	wheat	rice	sugarcane	potato
HHs without LPG	1280.8	1143.8	20560.9	7887.7
HHs with LPG	1485.4	1298.0	24449.4	10155.2
% increase in crop yields	16%	13%	19%	29%
Author's own household surveys				

c) Impact of reliable and cheap irrigation on agricultural production

Table 2.14 below presents field research observations on the irrigation water utilization by households. The table shows that HHs with personal irrigation pump, on an average gave 41% more water per acre in rice crop compared to HHs without personal irrigation pumps. However as shown in the same table below, the former spent significantly lower cost per acre of irrigation compared to latter. The same table also shows that HHs with irrigation pumps had higher crop output for crops like rice which is dependent on water. Provided reliable and cheap irrigation, HHs can significantly improve their crop output.

Table 2.14: Irrigation water usage by HHs with personal pump viz-a-viz HHs without personal pump

HH characteristics	wheat	rice	sugarcane	Potato
	hours of irrigation per acre (hours/ acre)			
HH dependent on water purchase	25	33	39	15
HH with own irrigation pump	28	46	47	23
	Money spent on irrigation per acre (Rs/ acre)			
HH dependent on water purchase	2152.89	3667.093	5349.333	1527.108
HH with own irrigation pump	1989.9	3099.823	3451.838	2319.454
	Crop output per acre (kgs/ acre)			
HH dependent on water purchase	1280.128	1098.595	23000	9080.905
HH with own irrigation pump	1477.513	1329.196	23462.56	9860.064
Author's own household surveys				

d) Solar Water Pump for Irrigation and food production

During the field research, an interview was conducted with a local farmer employing solar water pump (SWP) for irrigation. This farmer had received SWP in government subsidy program as discussed in section 2.2. It was observed that SWP had significant synergies with his food production. After getting solar water pump connection, the owner was motivated to cultivate vegetables such as Ridge gourd which gives significantly higher revenues per acre of crop (Rs 1,47,000/ acre compared to around Rs 20,000 – Rs 40,000 per acre with rice or wheat), however it needs significantly large amount of irrigation water (100 hours/ acre compared to 40 hours/ acre in rice crop). Moreover, the crop yields of this farmer were significantly higher, for instance 2.0 tonnes/ acre for rice compared to average of around 1.2 tonnes/ acre as observed in field research. He also uses this pump to sell water to neighbouring farms. During the time when irrigation pump is not used, the owner was exploring the opportunities of using the solar PV array of SWP to power his residential load or sell this electricity to nearby HHs. For the farmers using electric tube wells, it was observed that these farmers generally had to travel to their farms in the night time because electricity supply comes only in the night time and this makes them prone to animal attacks/ snake attacks and also impact their activities the following day. However, with solar water pump, the interviewed farmer was able to avert such risks.

e) <u>Energy crop plantation and the HHs income augmentation</u>

During the field research, it was observed that the villages which are close to the rivers for instance village MM and BM, have a soil type called "Balu mitti" in local language which needs lot of irrigation during summers which force HHs to leave their farms uncultivated during summer season. For instance, as observed in household surveys in village MM, 114 acres were cultivated in winters however in summers only 49 acres were cultivated. Similarly, in village BM, 128 acres were cultivated in winters and only 80 acres during summers and that too with lower productivity. Moreover, during FGDs in village MM, farmers mentioned that their soil is not strong enough to bear crops in both season. For such areas, opportunities can be explored to grow energy crops such as Sesbania, which needs less water and nutrient. The woody biomass produced can be used to run biomass-based power plants for the village and can also give an income generation for the farmers. In village MM and BM, an analysis can be made on the impact of household economics for the case when households are encouraged to grow Sesbania instead of leaving their farms uncultivated.

2.5 Summary of energy situation in rural Uttar Pradesh

Appendix table A2.1 presents the characteristics of energy systems (cooking, lighting, power and irrigation) in each surveyed village in UP, the summary of which is presented below.

Amongst the cooking energy systems, the most preferred household fuel across UP is the dung cake supported by firewood (or crop residues). Wood is the primary cooking fuel for majority of households in Rae Bareilly district (Central UP) whereas in other districts wood is increasingly becoming a supporting fuel with dung cake. Crop Residue is the major cooking fuel for majority of households in Eastern UP districts. Bioenergy markets are more prominent in Eastern UP district (Sant Kabir Nagar) where average household landholding and livestock endowment is small. Here, bioenergy market prices are higher compared to Western UP districts. During Monsoon, more number of households use LPG as primary fuel. There are several misconceptions with regards to LPG and biogas where food cooked in traditional bioenergy is perceived tastier and healthier by local households. Biogas is almost non-existent.

Among the lighting and electrical systems, kerosene is the lighting source for majority of the households. This is because of the highly unreliable grid electricity supply as well as the provision of highly subsidized kerosene by the government. Electricity thefts are observed everywhere but most predominantly in MP, BM and MM villages which are also the remote villages. Battery storage and solar technology is gaining more popularity amongst rich households in all surveyed villages because of declining solar technology prices and highly unreliable grid power. Whereas, cheap chinese lights (rechargeable battery-based lamps) are gaining more popularity among poor households.

Amongst irrigation system, private electricity tubewells are preferred choice by large landlords whereas diesel-based water pumps are preferred by medium sized landlords. Poor households and small landholders are majorly dependent on irrigation water markets where water is sold by private pump owners (large landlords). Private ownership of water pumps is higher in Western UP districts. Irrigation water markets are more prominent in Eastern UP districts where water purchase prices are higher compared to Western UP districts.

CHAPTER 3

3. FACTORS THAT IMPACT MODERN ENERGY TRANSITION AMONGST THE RURAL HOUSEHOLDS (HHS) OF UTTAR PRADESH (UP)

A large percentage of rural households in Uttar Pradesh (UP) are still dependent on traditional biomass for cooking and kerosene for lighting. Field research noted that on an average a rural household in UP consumed 1.7 tonnes of dung cakes, 0.9 tonnes of firewood, 0.17 tonnes of crop residues and 55.2 liters of LPG for annual cooking energy use (for household as well as livestock feed). This means that despite of several government initiatives on improving energy access in the state, majority of rural population in Uttar Pradesh continues to be dependent on traditional and dirty energy sources. Access to clean, affordable, reliable and adequate energy is a prerequisite for the sustainable economic development. To achieve sustainable development goals through improved energy provision, it is therefore very important to understand that how rural households take their energy usage decisions. A good understanding of the factors driving household energy consumption patterns can enable appropriate policy design and its implementation. This chapter attempts to analyze the factors which drive rural households in UP to make a transition to modern cooking and lighting energies. Section 3.1 of this chapter presents a literature review on the determinants of household energy choices. Section 3.2 identifies the research gaps and to overcome the same, it presents the conceptual framework which guides this empirical research. Section 3.3 presents the econometric models that are used for analyzing the determinants of energy transition and Section 3.4 discusses the empirical findings. Section 3.5 concludes the chapter and provides recommendations on the strategies that can aid in household's modern energy transition.

3.1 Literature Review on the determinants of energy transition

Conventional theories guiding the research on energy transition

The theory of energy ladder was an early approach for explaining the energy choice of households, which is based on the correlation between household wealth and the uptake of modern energy sources (Davis 1998, Barnes and Floor 1996, van der kroon et al. 2013). Here it is assumed that there is a ladder of energy preferences of households where dirty and inferior fuels (such as crop residues and dung cake) form the bottom stairs of the ladder, transition fuels such as kerosene and coal form the middle stairs whereas the modern and clean fuels (such as electricity) form the top stairs of the ladder. According to this theory, household behave as a utility maximizing consumer and as its income increases it moves to more sophisticated energy carriers towards the top of the ladder, abandoning the energy carriers at the bottom of the ladder (Barnes and Floor 1996, Davis 1998, Heltberg 2004, Van der kroon et al. 2013). However, using empirical evidences, several newer studies have challenged the theory of energy ladder. For instance, Masera et al. 2000 using a case study from Mexico observed that households do not completely give up traditional fuel with their rising wealth but rather use them along with more modern fuels. Fuel Stacking is the newer approach for explaining the household energy choice, which says that fuel switching by households is not uni-directional i.e. households may not completely switch from one fuel to another and instead use additional energy type without completely abandoning the energy type which it was using early (ibid). There are several factors that explains the fuel stacking behavior of households. Firstly, this way it is argued that the household strengthen its fuel security in case of disruption of modern energy supply fuel or fluctuations in their prices (Van der kroon et al. 2013). Davis 1998 argues that fuel stacking approach makes more sense for the poor rural households who have irregular incomes and therefore irregular usage of modern energy which needs handy cash. Masera 2000 also argued that fuel choices of household may not be completely driven by economic rationale but also by cultural and social preferences. Kowsari and Zerriffi 2011 quoting Heltberg 2004, argues that fuel stacking is more commonly practiced in rural regions of developing world, then in urban world.

<u>Recent literature on energy transition in India and the other parts of the world</u>

Household wealth has conventionally been regarded as the most important factor influencing the household energy transition to modern energies. In an Indian case study, Isaac and van Vuuren (2009) noted that poor households are less likely to adopt modern energy technologies in contrast to richer households. Besides household income, household demography also plays a major role in influencing household energy choice. Baiyegunhi and Hassan 2014 demonstrated the same in a case study from Kuduna state of Nigeria. For the analysis, it used the consumer utility maximization approach to frame a multinomial logit model. Empirical results of the study showed that household head's age, educational attainment, household size, income, type of dwelling unit, the duration of food cooked, and price of fuelwood are statistically significant factors influencing households' choice of cooking fuel. Lee et al. 2015 is a case study from Eastern Indonesia which proved that household energy choices are also affected by non-economic characteristics and external factors such as opportunities to sell firewood. Based on a case study of forest margin communities in eastern Indonesia, the study observed that modern fuel subsidy reform barely reduced rural household demand for fuelwood, rather it significantly increased fuelwood demand for local enterprises (such as agro-processing). Howells et al. 2010 presented the impact of markets, institutions, information failures on the energy transition by households. It argued that consumers (and producers) attempt to maximize their utility (or profitability) subject to constraints and as these constraints change, they impact the energy use patterns. It termed such constraints or change in constraints as circumstantial drivers, which include income, access to energy-appliance options, management or access of communal land, extent to which the local economy is monetized, institutional and policy intervention, location and climate, dwelling and cultural norms. The paper defined 3 categories of drivers that impact energy transition: 1) primary (Independent driver) which is derived from the increase in utility that the new energy source brings, 2) circumstantial drivers as discussed above, 3) consumer information on energy. Sehjpal et al. 2014 utilized Howell et al. 2010 to determine the range of factors that influence energy transition in India. Utilizing Logit modelling and household survey data from Madhya Pradesh province of India, ibid observed that apart from income, socio cultural factors impact the energy transition. It observed that formal employment of household woman positively impacts the fuel transition. It also observed that electricity access to the household and price of LPG play an important role in switching to a cleaner fuel. While the above discussed studies were country specific studies, Behera et al. 2015 tried to identify household energy change behaviors across different countries of South Asia viz India, Bangladesh and Nepal. It utilized microeconomic theory (based on consumer utility maximization principles) and formulated a multivariate probit model. Utilizing household survey data from the above 3 countries, the study found that the household head's age, gender, educational level along with the number of children, adult male and female members, household assets and wealth, and access to market affect households' energy choices. In Nepal and Bangladesh, it observed that more female members are engaged in fuelwood collection compared to India and the number of adult male members in the household was also found to influence fuelwood collection. While most household energy choice studies have used data for a single cross-section of households at a point in time, Burke and Dundas 2014 instead used national level longitudinal data to identify factors influencing household energy choice while controlling for country level causes of unobserved heterogeneity. The region of research of this paper is South Asia. The paper observed that while higher incomes are linked to modern energy usage, they are not associated with significant reduction of bio-energy. Secondly it observed that greater female labor force participation is associated with reduction in household bio-energy use, which means that the opportunity cost of woman's time is of importance for the household energy transition. It observed that an increase in South Asia's female labor force participation rate of 10 percentage points would likely be associated with a reduction in per-capita household biomass energy use of around 20%. Alem et al. 2016 analyzed energy choice determinants in the context of Ethiopia. The major innovation of this paper is that this paper utilized a panel multinomial logit approach which controls for unobserved heterogeneity and incorporates analysis of changes over time. The results of this research showed that household expenditure, price of energy commodities and household education play an important role in determining fuel choice. Drawing lessons from the existing literature on household energy transition, Van der Kroon et al. 2013 argues that there are three categories of factors that influence energy decisions of households: 1) country external factors that surrounds the society of the communities and these include climate, location and history, 2) decision context that forms household external factors and the country internal factors and these include institutional, political and market situation, 3) internal factors of the households based upon the characteristics and the factor endowment of the household. It further argues that the interaction between these categories influence the energy choice of households. There has also been literature on improving the robustness of econometric methodologies for analyzing the determinants of energy transition. For instance, Rahut et al. 2016 combines three years of data and uses the multivariate probit, Tobit and Heckman Two-Step Selection models. The paper uses Bhutan Living Standard Surveys from year 2003,2007 and 2012. The results showed that wealthier households and households with more educated members are likely to shift to cleaner energy. It observed that female-headed households are more likely to choose cleaner energy, and it also observed that the proximity of clean and a cost-effective source of energy to the household favors the transition to clean energy. In contrast to representative consumer approach followed in most of the above economic models, Ekholm et al. 2010 argued that the energy choice of consumers with different income and location (heterogenous household groups) should be assessed separately. Using Mas-Colell et al. 1995, it stated that "if the preferences are locally non-satiable and the utility function is continuous, a problem of minimizing costs to yield the similar amount of utility arrives at the same consumption choice and thus is an alternative formulation to the consumer choice problem". This study used Indian National Sample Survey (NSS) data and factors such as preferences and private discount rates for different group of households. Study identified the amount of capital subsidies on modern fuels such as LPG which can facilitate their partial and full penetration amongst rural and urban categories of households. The study also reported several limitations, for example, linear cost optimization approach proposes a single solution, whereas practically households use multiple fuels for cooking. Secondly, it ignored the fact that the fuel consumption is also dependent on physical access to modern fuels.

3.2 Conceptual Framework

Previous section discussed the energy ladder and fuel stacking theories, which have been used by the existing literature on household energy choice. However, these theories have some gaps. While analyzing household's energy use behavior, both the theories focus on household's consumer utility maximizing behavior which means that they emphasize mainly on the household's consumption side. However, it was discussed in chapter-1 that the household's energy choice decision is not just dependent on its consumption side but also its supply side because agricultural households are both suppliers and consumers of bioenergy. It was argued that there is a water-energy and food security (WEF) nexus around the household's energy choice and it takes its energy related decisions not in isolation but jointly with its food production and natural resource utilization. Lack of holistic approach in understanding the energy transition of households has also been highlighted in the recent literature. For instance, Kowsari and Zerriffi 2011 argues that the previous literature has utilized the following 4 different approaches for understanding the household energy choice behavior, however, there is a big dearth of literature that combine these and adopts an integrated approach: 1) physical-technical-economic models which include economic models that assume household to take energy decisions based on its utility maximizing behavior and technology models where changes in household energy usage pattern arise from the change in energy technologies, 2) psychology based approaches which suggest that household energy use decisions involve complex behavioral and social processes, 3) Sociological and anthropological models which advocate the influence of institutions, government policies, markets and social structures in household energy decision process, 4) Integrated approach which combines technological, economic, social and behavioral aspects of household energy use.

Mirzabaev et al. 2015 argues that the application of WEF nexus approach can be used as an integrated approach to understand household behavior on energy consumption. ibid also argues that analyzing these nexus issues requires an understanding of the household's activities and their interconnections. An agricultural household model (AHM) that utilizes the interconnection between its own production and consumption decisions, therefore provides a good solution. Pattnayak et al. 2004 argues that there is not much empirical literature on the analysis of energy determinants in the framework of AHM because such analysis needs extensive economic data at household level. ibid utilized AHM in understanding the firewood usage of Manggarai farming households in Indonesia. The study analyzed the shadow price of the fuelwood collection for the Manggarai farming households and found that the fuelwood collection and access to the forests significantly influence the household economy. It further argued that cost of forest access, wealth, park staff activity, schools and road and other developmental activities can significantly reduce the dependence of communities on the forests. Chen at al. 2006 utilized AHM to analyze the factors influencing household energy transition in rural China. Using AHM, it identified the following major set of variables that can impact the household energy use of firewood: stove characteristics, household characteristics such as size, education etc., characteristics of energy systems such as distance of wood source, household time endowment, agricultural production and the livelihood. Utilizing Ordinary least square and Tobit model on the household survey data, it observed that distance to the forest is negatively related to fuelwood consumption by the households with good market access. Moreover, the study also tried to analyze the behaviors of heterogeneous group of households. Guta 2014 applied AHM in a case study in Ethiopia to analyze the nexus between energy and food production. It observed that household's labor allocation for fuelwood collection is negatively associated with agricultural wage thus proving the fuel-food tradeoff from labor resource perspective.

The literature review indicates that there is a dearth of studies that use integrated approach to understand the drivers of energy transition in India. Based on the above discussions on using WEF nexus approach as an integrated approach for understanding household energy choices, following conceptual framework (as shown in figure 3.1) will be used in the research. It has 3 major depictions. Firstly, at the core, there is a household which is not isolated but interacts with other households and local markets. Secondly, it shows that the household takes its energy decisions jointly with its decisions on food production and natural resource utilization. The analysis of this WEF nexus requires the analysis of household's activities and their interconnections. To analyze these household's activities and their interconnections, research utilizes the integrated approach as suggested by Kowsari and Zerriffi 2011. This combines technological, economic, social, behavioral, anthropological and environmental aspects of household energy use in an interdisciplinary manner. Then, thirdly, it shows that there could be several factors/ drivers which influence household's activities and their interdependencies, and influence household's decision process for its energy choice. Based on the above discussions, following set of factors are considered which can impact household energy use: technological factors (such as surplus of bio-energy for household), economic factors (such as household's livelihood opportunities), sociological factors (such as impact of local institutions and policies), psychological factors (such as caste of household or mentality of household head), environmental & health factors (such as respiratory diseases in house) etc. These are depicted in figure 3.1 and are elaborated in subsequent section.

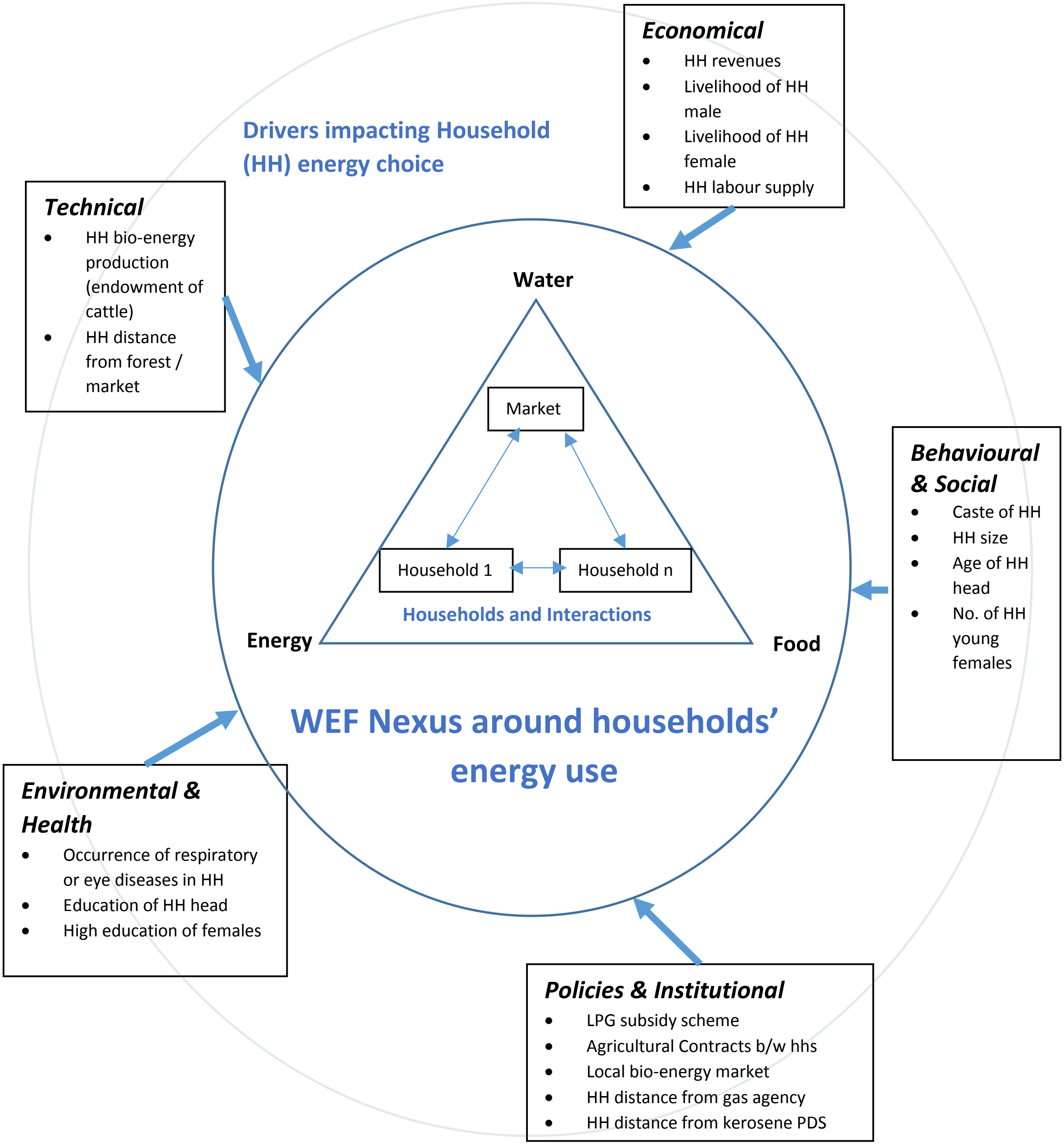

Figure 3.1: Conceptual Framework for analyzing the household (HH) energy choice behavior

3.3 Econometric Models for analyzing determinants of energy transition

In this section, different econometric techniques are used to analyze the factors that impact household's transition to modern energies for cooking and lighting. The analysis makes use of the household data from 380 households in Uttar Pradesh as discussed in Chapter 2. Following 2 econometric techniques have been used for the study:

Logit Model: Logit model (Logistic regression model) measures the relationship between categorical dependent variable and one or more independent variables by estimating probabilities, using logistic function which is a cumulative logistic distribution. For the logit model that analyzes the factors impacting transition to modern cooking energy, it is assumed that the household either chooses modern cooking energy (such as LPG or biogas) as the primary cooking energy which is designated by 1, or traditional cooking energy such as traditional bioenergy (crop residues, wood, cattle dung) as primary cooking energy which is designated as 0. For the logit model that analyzes the factors impacting transition to modern lighting energy, dependent variable takes the value of 1 if the household uses any modern lighting energy technology such as battery light or renewable energy-based light, and dependent variables takes the value of 0 otherwise. It is to be noted that lighting based on grid-based electricity is not included in the category of modern lighting because of the rampant stealing of grid-electricity, as observed during the household surveys. Since grid electricity was highly irregular, during power outages these households had to use kerosene-based lights or battery based lighting or renewable based lighting, so grid electricity connection was observed to be of no matter. The independent variables used in the model include the set of household characteristics which have been discussed in the above conceptual framework, and in the variable form they are enlisted in table 3.1 below, which are further elaborated after the table.

ZOIB model (Zero one Inflate Beta regression): Like logistic regression, beta regression is a type of generalized linear model (that allows linear model to be related to response variable via a link function) and here dependent variable could be any proportion between 0 and 1. Its uniqueness lies in the fact that its shape (beta distribution) can have lot of variations and is flexible. However, 0 and 1 are not possible values in beta distribution. ZOIB (Zero one inflated beta distribution) is an extension of beta regression and can even accommodate for these 0s and 1s. So, ZOIB has 3 processes:

- Logistic regression model for analyzing whether proportion equals 0 (so, it distinguishes between zeros and non-zeros in the proportion)
- Beta regression model for the proportion between 0 and 1 (not including 0 and 1)
- Logistic regression model for analyzing whether proportion equals 1 (so, it distinguishes between ones and non-ones in the proportion)

ZOIB model for modern cooking energy analyzes the factors that are associated with high proportion of modern input cooking energy (in MJ) in the total input cooking energy usage (in MJ) of the household. Zero inflate model for modern cooking energy analyzes the factors that are associated with zero proportion of modern cooking energy (in MJ) in total input cooking energy usage (in MJ) of household, while one inflate model for modern cooking energy analyzes the factors that are associated with 100% proportion of modern cooking energy (in MJ) in total input cooking energy usage (in MJ) of household. Consideration was made to construct ZOIB model to analyze the factors that are associated with high proportion of modern input lighting energy (in MJ) in the total input lighting energy usage (in MJ) of the household. However, widespread stealing of electricity grid supply makes the ratio of modern lighting to total lighting energy usage of household, an unreliable regressor. This can be explained with the following example. If an analysis is made on the ratio of modern lighting energy consumed by household (battery light or any renewable based lighting) to total lighting energy usage of household, then denominator comprising grid electricity-based lighting will affect this ratio. Here, it may be a case that a household who steals the grid electricity has lot of cheap power guzzler 100 W incandescent light bulbs which it uses carelessly when grid power is available. So, even if this household has lot of battery and solar based lighting for the time when grid electricity is not available, then high denominator will make this ratio useless for the analysis. Therefore, only logit model has been used for analyzing the factors impacting modern lighting energy transition of households.

Following section sets up the zoib and logit models for analyzing modern cooking and modern lighting energy transition of the households.

The Econometric Model

In the conceptual framework, discussions were made on various factors that may impact the energy usage decisions of the household. Utilizing the same discussions and the field research observations, following list of independent variables have been identified, as discussed in table 3.1 below. Continuing with the discussions in conceptual framework, table also highlights the category (driver category) that the chosen independent variables fall in. The primary category of the selected variables is highlighted by grey color, and light gray color represent their secondary category if applicable. Some variables may be used only for a specific model. The variables marked with single asterisk are not included in the logit model analyzing household's modern lighting transition as the reason could be their little expected correlation with dependent variable or their possible high correlation with another independent variables, and this will be discussed along with the explanation of variables in the next section. The variables marked with double asterisk are not included in the logit and zoib model analyzing household's modern cooking energy transition because of the same above discussed reasons. Section 3.4 presents the explanation of the independent variables and the results of the model.

Table 3.1: Independent variables for the models analyzing household's modern energy transition

S.No	Independent variables for model	Category of variables influencing energy transition					
		Technical	**Economical**	**Social, behavioural and cultural**	**Policies & Institutional**	**Health & Environmental**	**Households interactions**
1*	Number of cattles with hh (**CT**)						
2	HH's distance from nearest market (**MD**)						
3	Annual hh revenues (**RV**)						
4	Regular non-agricultural livelihood of hh male ($\mathbf{NL_m}$)						
5	Annual regular non-agricultural labor days of the hh females ($\mathbf{NL_f}$)						
6	HH size (**HS**)						
7	HH's caste ($\mathbf{CS_{hh}}$)						
8*	High education of hh female ($\mathbf{ED_{fm}}$)						
9*	HH head's years of education ($\mathbf{ED_{hd}}$)						
10	HH head's age (**AG**)						
11	HH dwelling type (**DW**)						
12 **	Presence of young women in hh (**NF**)						
13 **	Years of education of hh's highest educated member ($\mathbf{ED_{hh}}$)						
14 **	Caste of village chief of the hh ($\mathbf{CS_{vc}}$)						

S.No	Independent variables for model	Category of variables influencing energy transition					
		Technical	**Economical**	**Social, behavioural and cultural**	**Policies & Institutional**	**Health & Environmental**	**Households interactions**
15*	HH's purchase price of dung cake in local market (**DP**)						
16	Agricultural contracts of hh ($\mathbf{AL_f}$)						
17*	HH's possession of LPG stove through government scheme ($\mathbf{PD_l}$)						
18 **	HH's distance from PDS kerosene shop ($\mathbf{PD_k}$)						
19	Occurrence of respiratory or eye problems in hh (**HT**)						

* this variable is not included in the logit model for modern lighting energy.
**this variable is not included in the logit and zoib model for modern cooking energy.
Note: Dark shades represent the main category of independent variables & light shade represent their secondary category if applicable.

While selecting suitable variables for these model, household's farm size was also thought to be an important variable, but since household's farm size was observed to be correlated with annual household revenues, it has been excluded from the list of selected variables. Since household's distance to forest is negatively correlated to household's distance to market, therefore the same has also been excluded from the list of selected variables. Also, the household's distance to gas agency is positively correlated with household's distance to market as probability of gas agency in the main markets is high, therefore it has also not been included in the variable list.

Representation of the econometric models used in the analysis

Based on the above discussions, following econometric models have been formulated:

Logit Model 1:

$$\text{Logit (MC)} = \alpha + \beta1\text{ (CT)} + \beta2\text{ (MD)} + \beta3\text{ (RV)} + \beta4(\text{NL}_\text{m}) + \beta5(\text{NL}_\text{f}) + \beta6(\text{HS}) + \beta7(\text{CS}_\text{hh}) + \beta8(\text{ED}_\text{f}) + \beta9(\text{ED}_\text{hd}) + \beta10(\text{AG}) + \beta11(\text{DW}) + \beta12(\text{DP}) + \beta13(\text{AL}_\text{f}) + \beta14(\text{PD}_\text{l}) + \beta15(\text{HT}) \qquad (3.1)$$

Where, MC is household's utilization of modern cooking energy as its primary cooking fuel.

Logit Model 2:

$$\text{Logit (ML)} = \pi + \gamma1\text{ (MD)} + \gamma2\text{ (RV)} + \gamma3(\text{NL}_\text{m}) + \gamma4(\text{NL}_\text{f}) + \gamma5(\text{HS}) + \gamma6(\text{NF}) + \gamma7(\text{CS}_\text{hh}) + \gamma8(\text{ED}_\text{hh}) + \gamma9(\text{DW}) + \gamma10(\text{AL}_\text{f}) + \gamma11(\text{PD}_\text{k}) + \gamma12(\text{CS}_\text{vc}) + \gamma13(\text{HT}) \qquad (3.2)$$

Where, ML is household's utilization of modern lighting energy.

Zoib Model 1:

$$\text{ZOIB (RMC)} = \mu + \delta1\text{ (CT)} + \delta2\text{ (MD)} + \delta3\text{ (RV)} + \delta4(\text{NL}_\text{m}) + \delta5(\text{NL}_\text{f}) + \delta6(\text{HS}) + \delta7(\text{CS}_\text{hh}) + \delta8(\text{ED}_\text{f}) + \delta9(\text{ED}_\text{hd}) + \delta10(\text{AG}) + \delta11(\text{DW}) + \delta12(\text{DP}) + \delta13(\text{AL}_\text{f}) + \delta14(\text{PD}_\text{l}) + \delta15(\text{HT}) \qquad (3.3)$$

Where, RMC is ratio of household's modern cooking energy utilization (MJ) in its total cooing energy mix (MJ).

Like Zoib model 1, Zeroinflate1 and Oneinflate1 models have been formulated with the same variables.

3.4 Results and discussions

Household characteristics

Before discussing the model variables and model results, descriptive statistics of major household characteristics are presented in table 3.2 below.

Table 3.2: Descriptive Statistics (Characteristics of the households)

Household characteristics	Mean	Std. Dev.	Min	Max
Annual Revenues (Ten thousand Rs)	22.39	28.51	1.19	319.62
Annual dung cake consumption (kgs)	1728.57	1035.38	0	6000
Annual firewood consumption (kgs)	874.47	723.01	0	4560
Annual crop residues consumption (kgs)	169.59	287.89	0	2400
Annual LPG consumption (kgs)	55.28	75.77	0	504
Monthly energy consumption from renewable sources and battery (MJ)	19.42	52.82	0	356.40
Monthly kerosene energy consumption (MJ)	107.69	46.39	0	305.52
Number of cattles (Nos)	1.48	1.58	0	11
Distance from nearest market (km)	6.57	3.03	1	11
Regular non-agricultural based livelihood of HH male (Yes/ No)	0.39	0.49	0	1
Annual regular non-agricultural labour days of the hh females (days)	11.25	45.71	0	365
Household size (nos)	6.84	2.95	1	18
Upper caste of the hh (Yes/No)	0.31	0.46	0	1
High education (graduation) of hh female (Yes/ No)	0.14	0.35	0	1
Household head's years of education (years)	5.51	5.52	0	19
Household head's age (years)	49.71	12.77	18	82
Dwelling type permanent (Yes/ No)	0.82	0.38	0	1
Number of young women in hh (Nos)	1.20	1.03	0	5
Years of education of highest educated member (years)	10.21	4.98	0	19
Upper caste of village chief of hh (Yes/ No)	0.29	0.46	0	1
Purchasing price of dung cake in household's local market (Rs/ kg)	5.54	1.63	1	8
Agricultural contracts of households (days per year)	19.82	31.77	0	200
Possession of LPG stove through government scheme (yes/ no)	0.40	0.55	0	4
Distance from PDS kerosene shop (kms)	1.70	2.11	0	6
Occurrence of respiratory or eye problems in HH (yes/ no)	0.10	0.30	0	1
Source: Author's household survey data				

Determinants of household's modern energy transition

Table 3.3 and Table 3.4 below presents the results (significance level as well as marginal effects) of the logit model 1 and zoib model 1 respectively that analyze the factors impacting household transition to modern cooking energies. Table 3.5 presents the results of the logit model 2 that analyzes the factors impacting household transition to modern lighting energies. These are followed with the discussions on the results.

Table 3.3: Results of the logit model 1 analyzing modern cooking energy transition of the household

S.No	Variables	Logit Regression		Marginal effects in Logit Regression	
		Coef.	P>z	Coef.	P>z
1	Number of cattles with HH (CT)	-0.240	0.147	-0.0160	0.139
2	Distance of hh from nearest market (MD)	-0.225	0.003**	-0.0150	0.001**
3	Annual Household (HH) Revenues (RV)	0.022	0.008**	0.0015	0.005**
4	Regular non-agricultural based livelihood of HH male (NL_m)	1.293	0.005**	0.0860	0.003**
5	Annual regular non-agricultural labor days of the hh females (NL_f)	-0.003	0.471	-0.0002	0.469
6	HH size (HS)	-0.149	0.072*	-0.0099	0.065*
7	Caste of the hh (CS_{hh})	0.589	0.247	0.0392	0.244
8	Higher education of hh female (ED_{fm})	0.966	0.094*	0.0643	0.086*
9	Household head's years of education (ED_{hd})	0.082	0.052*	0.0055	0.045**
10	Household head's age (AG)	0.014	0.465	0.0009	0.464
11	Dwelling type (DW)	0.228	0.744	0.0152	0.743
12	Price of dung cake in local market (DP)	0.452	0.003**	0.0301	0.002**
13	Agricultural contracts of household females (AL_f)	-0.030	0.093*	-0.0020	0.091*
14	Possession of LPG stove through government scheme (PD_l)	3.073	0.000***	0.2045	0.000***
15	Occurrence of respiratory or eye problems in HH (HT)	0.510	0.535	0.0339	0.534
*** significant at 1% level, ** significant at 5% level, * significant at 10% level					

Table 3.4: Results of the Zoib model 1 analyzing modern cooking energy utilization of the household

S.No	Variables	Zoib Regression		Marginal effects in Zoib		Zero Inflate Regression		One Inflate Regression	
		Coef.	P>z	dy/ dx	P>z	Coef.	P>z	Coef.	P>z
1	Number of cattles with HH (CT)	-0.118	0.031**	-0.0046	0.038**	0.231	0.259	-1.089	0.028**
2	Distance of hh from nearest market (MD)	-0.083	0.000***	-0.0032	0.000***	0.133	0.152	-0.230	0.122
3	Annual Household (HH) Revenues (RV)	0.004	0.017**	0.0002	0.023**	-0.009	0.779	0.014	0.250
4	Regular non-agricultural based livelihood of HH male (NL_m)	0.265	0.034**	0.0106	0.036**	-1.464	0.014**	0.018	0.983
5	Annual regular non-agricultural labor days of the hh females (NL_f)	-0.001	0.467	0.0000	0.466	0.502	0.994	-0.174	0.990
6	HH size (HS)	-0.077	0.001***	-0.0030	0.001***	0.044	0.692	-0.233	0.201
7	Caste of the hh (CS_{hh})	0.083	0.521	0.0033	0.526	-0.902	0.166	-1.013	0.258
8	Higher education of hh female (ED_{fm})	0.347	0.016**	0.0149	0.029**	-0.210	0.833	0.120	0.885
9	Household head's years of education (ED_{hd})	0.026	0.025**	0.0010	0.029**	-0.011	0.860	0.096	0.233
10	Household head's age (AG)	-0.013	0.023**	-0.0005	0.024**	0.005	0.812	0.072	0.060
11	Dwelling type (DW)	0.082	0.701	0.0031	0.695	-0.158	0.831	-0.712	0.592
12	Price of dung cake in local market (DP)	0.161	0.000***	0.0063	0.000***	0.149	0.458	-0.257	0.196
13	Agricultural contracts of household females (AL_f)	-0.004	0.297	-0.0001	0.290	0.011	0.238	0.004	0.904
14	Possession of LPG stove through government scheme (PD_l)	0.723	0.000***	0.0283	0.000***	-181.409	0.994	1.261	0.115
15	Occurrence of respiratory or eye problems in HH (HT)	0.190	0.452	0.0079	0.477	-0.141	0.845	-1.426	0.334
*** significant at 1% level, ** significant at 5% level, * significant at 10% level									

Table 3.5: Results of the logit model 2 analyzing modern lighting transition of the household

S.NO	Variables	Logit Regression		Marginal effects of Logit Regression	
		Coef.	P>z	Coef.	P>t
1	Distance of hh from nearest market (MD)	-0.328	0.000***	-0.0312	0.000***
2	Annual Household (HH) Revenues (RV)	0.033	0.000***	0.0031	0.000***
3	Regular non-agricultural based livelihood of HH male (NL_m)	1.427	0.000***	0.1356	0.000***
4	Annual regular non-agricultural labor days of the hh females (NL_f)	0.009	0.002**	0.0009	0.002**
5	HH size (HS)	-0.138	0.076*	-0.0131	0.072*
6	Number of young females in hh (NF)	0.104	0.613	0.0099	0.613
7	Caste of the hh (CS_{hh})	-0.058	0.887	-0.0055	0.887
8	Education years of highly educated hh member (ED_{hh})	0.020	0.648	0.0019	0.648
9	Dwelling type (DW)	0.374	0.535	0.0355	0.535
10	Agricultural contracts of household females (AL_f)	-0.013	0.106	-0.0012	0.105
11	HH distance from kerosene PDS shop (PD_k)	0.020	0.800	0.0019	0.800
12	Upper Caste of Village Chief (CS_{cv})	0.746	0.063*	0.0709	0.059*
13	Occurrence of respiratory or eye problems in HH (HT)	-0.061	0.918	-0.0058	0.918
*** significant at 1% level, ** significant at 5% level, * significant at 10% level					

<u>Explanation of model variables and the discussions on the results</u>

This section discusses the results of the econometric models. For each of the independent variables used in the model, firstly its brief explanation is presented, followed by the discussion on its econometric results.

Number of cattles with household (hh): This is the number of cows/ buffalos (male or female) with the household. This variable clarifies that how a household takes energy related decision with respect to its agricultural production, for example whether it prefers to use its cattle dung for producing dung cakes (traditional bio-energy) or biogas for cooking energy or use it as farm fertilizer, depending on its farm needs, taste characteristics and energy needs. The results of logit model 1 does not shows any significant correlation between household's number of cattles and its cooking energy utilization.

However, results of zoib model 1 suggest that within 95% confidence interval, if household is using modern cooking energy, then every increase in the number of household cattles is associated with 0.46% decrease in the proportion of household's modern cooking energy usage (in MJ) in its total cooking energy mix (in MJ), while keeping all other variables constant. Within 95% confidence interval, one inflate model suggests that higher number of household cattles is negatively associated with 100% proportion of modern cooking energy (in MJ) in its total cooking energy usage (in MJ). The results of logit and zoib model indicate that the number of household cattles is not definitely associated with the modern cooking energy transition of household but larger number of cattles and hence greater amount of cattle dung production motivates household to use lesser amount of LPG based cooking and compensate it with the dung cake-based cooking. The possible reasons could be that if the household has more number of cattles, then it may have cattle dung surplus then what may be required in its farm, or it find using dung based cooking more rationale then using it as farm fertilizer as it already gets subsidized urea and NPK (Nitrogen-Phosphorous and Potassium) fertilizers from the government, or it views crop production as side business with livestock rearing being the main livelihood so it is not much worried about crop production, or household needs to cook feed for the large number of livestocks for which it needs high amount of dung based cooking. It is to be noted that the household with cattle dung surplus could have shifted to biogas, however during the field research, it was observed that the biogas technology is perceived as failed technology by the households and they didn't want to experiment with the same.

Household's (HH's) distance from nearest market (in kms): The market is the place where regular gathering takes place for the sale and purchase of agricultural products, livestock products, labor market and other commodities such as energy technologies or other market products. With proximity to markets, households are expected to have more employment opportunities and hence more opportunity cost of time, and this variable clarifies the influence of household's opportunity cost of time on household's energy choice. Within 99% confidence interval, results of logit model 1 and logit model 2 suggests that this variable is statistically significant and negatively correlated with modern cooking energy transition as well as modern lighting energy transition. This means that if household is remotely located then it has lesser probability of shifting to modern cooking and modern lighting energy. Marginal effects in logit model 1 and logit model 2 suggests that with every 1 km increase in market distance, the probability of household using modern cooking energy as primary cooking fuel decreases by 1.5%, and the probability of household using modern lighting decreases by 3.1% respectively, while holding all other variables constant. Within 99% confidence interval, results of zoib model 1 suggests that if household is using modern cooking energy, then every 1 km increase in market distance from the household, is associated with 0.32 % decrease in the proportion of household's modern cooking energy usage in its total cooking energy usage, holding all other variables constant. There could be several reasons behind this behaviour. The following table 3.6 presents the average wage rates for different labour categories (off farm agricultural and non-agricultural) in different surveyed villages which are located at different distances from the market. The table shows that the households (villages) which are closer to the markets/ district headquarters have more opportunities of non-agricultural employment depicted by column e and have higher wages (column c and d), which makes their opportunity cost of time higher and this demotivates them to spend time on traditional energy collection and therefore they shift to modern energy.

Table 3.6: Correlation between market distance and household employment opportunities

a	b	c	d	e
Surveyed Villages	Distance of village from the market (kms)	Male off-farm agricultural wage in village (Rs/ day)	Female Off farm agricultural wage in village (Rs/day)	Non-Agricultural male labour days per HH per year (days) #
MG	7	150	100	265.2
OK	3	180	120	364.7
MP	11	150	70	243
BM	9	150	70	341
MH	1	250	180	133.83**
MA	5	200	150	137.89
MM	10	200	180	236.21*
NV	3	200	150	280.7

Source: Author's own field surveys
Note: * This is an exception because it is close to the touristic city of Vrindavan, so there are growing development in the areas
** this village has wealthy and large landlords with nuclear families which put more emphasis on education on youths, that's why non-agricultural male labour per HH is low
# Average number of males per HH in Uttar Pradesh is 2.2

Further, households with proximity to markets also have high tendency to use personal solar, battery banks and Chinese lights, for instance village MH, NV and MG (Table 2.5). This is because they have high interactions with the market, have more business contacts, have greater bargaining opportunities, they are more up to date with the market developments, and they have lesser transaction costs in market purchase. Further, households which are far from market/ district centre and have electricity lines passing through their areas, have more tendency for power stealing because such villages are less likely to get surprise checks from electricity department, and this demotivates them to buy modern lighting technologies such as solar etc. Households which are close to market or district headquarter have more opportunities of non-agricultural labour which means they have regular income/ handy cash for getting LPG/ electricity connection and paying their regular fees, whereas households in remote villages are majorly dependent on agriculture and have unpredictable incomes which are dependent on farm output. Moreover, gas agency or electric utility offices are generally closer to District Head Quarter, therefore households living closer to district head quarter have greater pursuing opportunity for the gas or electricity connection and have lesser transportation costs for cylinders. During the field surveys, it was observed that households which were staying away from gas agency had to pay Rs 30 per cylinder for the transportation of gas cylinder where the cost of recharging LPG cylinder (14 litres) was Rs 450.

Annual household (hh) revenues (in the unit of ten thousand Rs)): This is the sum of annual household revenues from its agriculture (crops and livestock), off farm labor (agricultural and non-agricultural), salaried job, business and remittances. The results of logit model 1 shows that within 95% confidence interval, every 10,000 Rs increase in annual household revenues increases its probability of using modern cooking energy as its primary cooking energy type by 0.15 %, while holding all other variables as constant. Within 95% confidence interval, results of ZOIB model 1 shows that if household is not meeting its 100% cooking energy demand with modern cooking energy, then every 10,000 Rs increase in its annual revenues is associated with 0.02% increases in the proportion of household's modern cooking energy usage in its total cooking energy mix, while keeping all other variables constant. Results of logit model 2 shows that within 95% confidence interval, every 10,000 Rs increase in annual household revenues, increases the probability of household using modern lighting energy by 0.31%, while holding all other variables as constant. There could be several reasons behind this behaviour. With growing wealth, household can more easily afford modern energy devices, services and their recurrent costs. For instance, to get an LPG connection, household needs to pay an upfront cost of around Rs 4500 and thereafter must pay around Rs 32 per litre for LPG gas. Similarly, the power storage batteries cost upto Rs 75 per Ah capacity. Further, if the household lives in remote location, then getting LPG connection/ modern electricity system could be even costlier and this demotivates the household from shifting to modern cooking or lighting energy. In addition, using modern energy system is also considered as show of supremacy by wealthy households. The positive correlation between modern cooking energy usage and household income in context of rural India and other parts of the world has also been documented by several studies in the literature, for instance Rahut et al. 2014, Sehjpal et al. 2014, Isaac and van Vuuren (2009), Baiyegunhi and Hassan 2014, Bahera et al. 2015. Further, Lay et al. 2012 in a setting of Kenya observed the positive correlation between household transition to modern lighting (such as solar home system) and household income.

Regular non-agricultural based livelihood of any of the household (hh) male**:** This is a categorical variable, which takes value of '1' if at-least one of the household male is involved in regular and stable non-agricultural livelihood such as government job, private job or a regular business, whereas it takes value of '0' if none of the household male is involved in such activities. This variable explains that how different types of livelihoods impact household energy choices. The results of logit model 1 show that within 95% confidence interval, presence of atleast one household male with regular non-agricultural work, increases the probability of household using modern cooking energy as its primary cooking energy type by 8.6 %, while holding all other variables constant. Within 95% confidence interval, ZOIB model 1 shows that when household is not meeting its 100% cooking energy demand with modern cooking energy, then presence of household male with regular non-agricultural employment is associated with 1.06% increase in the proportion of household's modern cooking energy usage in its total cooking energy mix, keeping all other variables constant. Within 95% confidence interval, the zero-inflate model 1 shows that absence of household male in non-agricultural regular work is associated with probability of household using 0% of modern cooking energy for its cooking energy demand. Results of logit model 2 shows that within 95% confidence interval, presence of household male with non-agricultural regular employment, increases the probability of household using modern lighting energy by 13.56%, while holding all other variables constant. There could be several reasons in support of the above results. These households have regular and higher wage job, therefore that they have regular and predictable income to pay for energy systems and energy services, unlike households dependent on agriculture. During the surveys, average wage of a regular salaried job male was observed to be around Rs 370/ day whereas with other livelihoods it was lesser and unpredictable (for instance Rs 245 / day and Rs 177/ day for irregular non-agricultural labour and irregular agricultural labour respectively). This means that households which have their members involved in regular non-agricultural work opportunities have higher opportunity cost of time or give more value to the household leisure and this demotivates them from spending time for traditional energy collection and therefore shifts to modern energy. Further, such households have males which work in factories, offices, enterprises or have close association with markets so they have greater market information of new technologies such as solar and have greater market interaction and lesser transaction costs to purchase modern energy as gas agencies or solar shops or battery shops are majorly located in the market areas. Another reason for greater consumption of LPG by such households could be that females in such households have to make quick food in the morning for the males who leave early morning for work. Further, as such households are less involved in agriculture, they have less opportunities with animal dung and agricultural residues. In the case study of Madhya Pradesh, India Sehjpal et al. 2014 observed the same phenomenon that the households where primary livelihood of male members involves regular and stable job, had greater tendency to shift to modern cooking energy as its primary cooking energy type. Figure 3.2 below shows the association of modern energy usage and household's regular non-agricultural work opportunity. It shows that out of the total number of households which use LPG as primary cooking fuel, around 80% of them have at least one male worker involved in regular non-agricultural job. Similar results are for households with personal big solar systems and HHs with personal battery backup system.

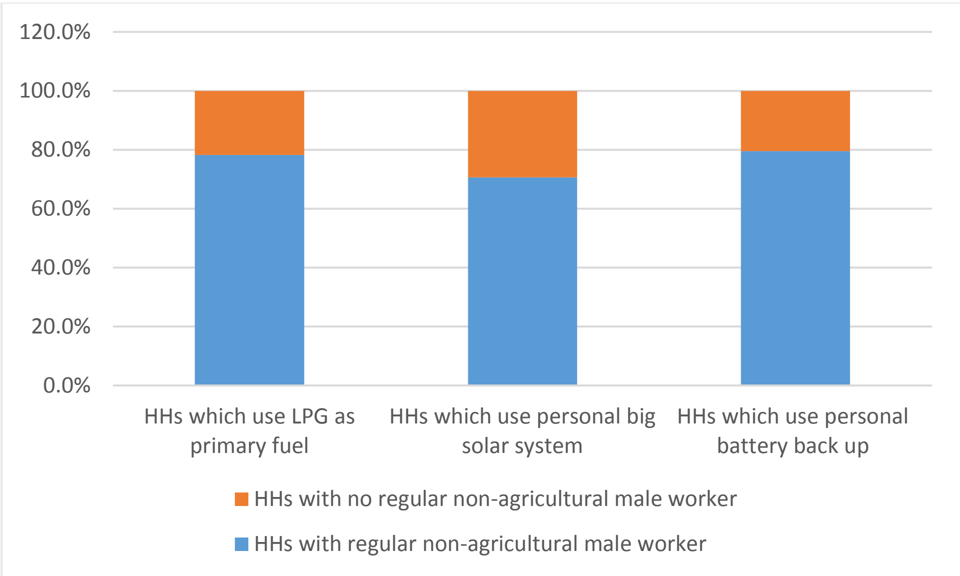

Figure 3.2: Household's energy usage and its non-agricultural work opportunities
Source: Author's own field surveys

Annual regular non-agricultural labor days of the household (hh) females: This is the summation of annual number of days that household's females spend on non-agricultural labor job. The results of logit model 1 and zoib model 1 indicates that the non-agricultural work of household female has no significant relation with its modern cooking energy transition. The possible reasons are as follows. Firstly, it can happen that even if a household female is involved in non-agricultural employment, but other household females are still house wives and they take care of traditional energy collection. Secondly, non-agricultural labour employment for females in the surveyed villages were observed to be limited to teachers, cooks, cleaners, maids in the local areas and with these jobs they are not exposed to markets and the information on modern energy technologies. Thirdly, it was observed that the household males associate food cooked in traditional energy with better taste and household females care more for the taste of males rather than the ill effects of traditional cooking on their own health. On the other hand, results of logit model 2 indicates that within 95% confidence interval, each one-day increase in the non-agricultural labour days of household female, increase the probability of household utilization of modern lighting by 0.1%, while holding all other variables constant. The possible reasons could be that such household female who work as maid in rich household see its master's family enjoying TV or better light or fan service, and then she demands similar energy services at her own home. Unlike the case of modern cooking energy where household male opposes female's demand due to his taste preference, he doesn't oppose the demand to purchase modern lighting or electricity system.

Household size *(in numbers)****:*** This is the size of household in numbers. This variable clarifies that how labor endowment of household impacts its energy choice. Results of logit model 1 suggests within 90% confidence interval, every 1-member increase in household size, decreases its probability of using modern cooking energy as primary cooking energy source by 0.99%, while holding other variables constant. Zoib model results indicates that within 99% confidence interval, every 1-member increase in household size is associated with 0.30% decrease in the proportion of household's modern cooking energy usage in its total cooking energy usage, while holding all other variables constant. Logit model 2 suggests that within 90% confidence interval, every 1-member increase in household size decreases the probability of household using modern lighting by 1.3%, keeping all variables constant. There could be the following reasons for the above discussed results. If the household is bigger in size, than it has higher cooking and lighting energy demand, and this makes it difficult to cash purchase LPG or modern electricity system for meeting its demand. Second reason could be that such household has greater number of females or children or males which can aid in the collection of traditional energy, or with joint families it gets more quota from the government for the purchase of kerosene for lighting. Another reason could be that the bigger families are the joint families who also have grandparents. During the survey, it was observed that grandparents (old people) have the perception that the food cooked in traditional energy has better taste, is good for the health and therefore they insist for the food cooked in LPG or modern biogas stove. Further, this behaviour may be the result of the internal politics in the household (eg. joint families), for example, there could be a case that there are several brothers in a joint family and some of them have different preferences on spending money, for instance, one brother spends more money on alcohol and the other brother wants to purchase a solar power system, however, the second brother thinks that If he invests in some modern energy system then why should the family of another brother (spending money on alcohol) enjoys the benefits of modern energy and therefore this demotivates him to invest in some modern energy system.

Household's (HH's) caste: This category includes '1' for upper caste households and '0' for lower caste household. The objective of this variable is to analyze the importance of household's social status in its cooking and lighting energy choice behavior. Following castes are included in the upper caste: Brahmins (Intellectuals), Rajputs (Kshatriya or the fighters), Vaishnava (Merchants). In Uttar Pradesh, with its caste appeasement politics, government put "Jaat" community under backward castes as government gives lot of social benefits to the backward castes. However, in other states, "Jaat" is not included in backward caste. In the field research, Jaats were observed to be amongst the economically forward castes and therefore they have been included in the upper caste in this research. Following castes are included in the backward caste/ non upper castes as observed in the survey: Scheduled Castes (Dalits), Yadavs (Cattle herders), Pal (Cattle herders), Bhagel (Cattle herders), Valmiki (Sweeper), Sunar (Gold Smith), Lauhar (Iron Smith), Kurmis (Farmers), Rajbhars (backwards). Muslims have also been included in the lower castes because of their low economic status as observed in the research and because of their demand to the government to get included in lower caste. In the field research, 116 households out of 380 households were the upper caste HHs. The results of logit model 1, logit model 2 and zoib model 1 don't show any significant correlation between household caste and household transition to modern cooking energy or modern lighting energy. Table 3.7 could be a reason for that. As per the field research, upper caste households have higher endowment of livestocks, private trees and farm areas, so they have greater and easier access to wood, dung and crop residues. They further have access to cheap labour from lower caste households who process the biofuels and take some percentage of bioenergy as fees for the labour. All the above reasons, along with taste consideration of food cooked in traditional cook stoves motivates upper caste household to continue using traditional cooking energy. For modern lighting, since upper caste households have more clout in the region, they openly steal grid power and manage to get government funded solar street lights in front of their houses.

Table 3.7: Characteristics of upper caste and lower caste households

Household characteristics	Lower Caste HH	Upper Caste HH
Private tree per hh (Nos)	12.1	37.2
Farm size per hh (acres)	0.94	3.71
No. of cattles per hh	1.08	2.44
Source: Author's own field surveys		

High education of household (hh) female: This is a categorical variable which takes the value of "1" if the highest education of any household female is graduation or above and it takes the value "0" otherwise. This variable is not included in logit model 2 (modern lighting transition) because this model already includes the variable on "education years of highest educated member" and including "high education of household female" would result in correlation errors. Whereas for cooking energy transition, impact of education of household female and household head are required to be analyzed separately and moreover household heads are generally household males and therefore little correlation is expected between them. Results of logit model 1 suggests that within 90% confidence interval, presence of household female with graduation degree increases the probability of household using modern cooking energy as primary cooking energy by 6.4%, while holding all other variables constant. Results of Zoib model 1 suggests that when household is not meeting its 100% cooking energy demand with modern cooking energy, then within 95% confidence interval, the presence of household female with graduation degree is associated with 1.4% increase in the proportion of household's modern cooking energy usage in its total cooking energy mix, while holding all other variables constant. While Sehjpal et al. 2014 in their study in Madhya Pradesh province of India observed the education level of household male and female insignificant for its modern energy transition, Pundo and Fraser 2006 in its study in Kenya observed the education level of household female significant for its modern energy transition which is in line with this finding. The reason for the result could be that when there is a highly qualified female in the household, she understands the ill effects of traditional cooking energy and with her respect in the household, she convinces other household members to switch to modern cooking energy.

Household head's (HH's) year of education: This variable captures the number of years of education of household head. For example, if household head is 5th grade pass, then he/ she has 5 years of education. This variable is not included in logit model 2 (modern lighting transition) because it already includes the variable "education years of highest educated household member" and including this variable would have resulted in correlation errors. Results of Logit model 1 shows that within 90% confidence interval, household head's high education has positive influence on household's transition to modern cooking energy, and each one-year increase in household head's education increase the probability of household shifting to modern cooking energy as its primary cooking energy type by 0.55%, while holding all other variables constant. Result of Zoib model 1 indicates that when household is not meeting its 100% cooking energy demand with modern cooking energy, then within 95% confidence interval, every one-year increase in household head's education is associated with 0.1% increase in the proportion of household's modern cooking energy usage in its total cooking energy usage. With higher education, household head is aware of the harmful effects of indoor pollution and this motivates him to switch to modern cooking energy. Other reason could be that with high education, the livelihood opportunities increase for the household head and with growing incomes, household can now afford modern cooking energy. Also, with high education and growing livelihood opportunities, opportunity cost of household head's time increases, and this demotivates household in spending time on bioenergy collection. Other reason could be that highly educated household head want to give good education to his/ her children and want them to spend time on education rather than bioenergy collection.

Household head's (HH's) age: This is the household head's age in year. Older household head is expected to have old thinking and misconceptions on cooking energy usage as discussed in chapter - 2 and the same behaviour is expected to be analysed with this variable. While logit model 1 (modern cooking energy) does not gives any significant results, results of zoib model 1 indicates that within 95% confidence interval, if household is using modern cooking energy, then every one-year increase in the household head's age is associated with 0.05% decrease in the proportion of household's modern cooking energy usage in its total cooking energy mix, while keeping all other variables constant. During the household surveys, it was observed that locals perceive food cooked in traditional bioenergy more healthier and tastier and that the smoke from the traditional cook stove kills the germs in the food. This perception was more prominent amongst elder people. During the field research, one local unqualified doctor (quack) even said that eating food cooked with modern cook stoves gives acidity. All these misconceptions stem out from old thinking of the people and therefore households led by elderly male or female prefer to cook food in traditional cook stoves.

Household's (HH's) dwelling type: This is the housing type of the household. This takes value "0" when the housing is a temporary structure such as an open hut or mud house with thatched roof, and it takes the value "1" when the housing is a permanent structure such as house made with concrete. The temporary housing structure of the household may demotivate household in making investments in modern energy systems, and the same behaviour is expected to be tested with this variable. Both logit and zoib model indicate insignificant correlation between dwelling type and the cooking energy and lighting energy choice of the household.

Household's (HH's) purchase price of dung cake in local market: This variable deal with the local bioenergy markets and the endowment of natural bioenergy resources locally and their institutions. The price of cattle dung cake (in Rs/ kg) in the local market is used as its proxy because in the field research, cattle dung was observed to be the most important bioenergy fuel and if there is a scarcity of cattles and forests/ private trees in or near the village, the price of dung cake in the local market is expected to be high and this may motivate the households to shift to modern cooking energy. The same behavior is expected to be tested with this variable. Within 95% confidence intervals, both logit and zoib model results show positive correlation between price of dung cakes in local market and transition to modern cooking energy. The marginal effects on logit model 1 suggests that with every 1 rupee increase in the price of dung cake in local markets, the probability of household's utilization of modern cooking energy as primary cooking fuel increases by 3.01%, while holding all other variables as constant. The marginal effects on zoib model 1 suggests that when household is using modern cooking energy, then with every 1 rupee increase in the price of dung cake in local market increase the proportion of modern cooking energy in total cooking energy usage of household by 0.63%, while holding all other variables constant. The above results can be explained by table 3.8 below. It shows that if the price of dung cakes in the local market is high (row A), then there is lesser number of cattles per HH in these villages (row B) and there is a scarcity of other resources such as wood (row C and D), and this pushes households to look for alternate energy sources for cooking. For instance, villages MG and OK have scarcities of cattles as well as wood resources but have higher percentage of households using LPG cooking gas as their primary cooking fuel.

Table 3.8: Correlation between household (hh) energy usage and local bioenergy markets

S.No	**Characteristics of HHs in the villages**	**Surveyed Villages**							
		MG	OK	MP	BM	MH	AY	MM	NV
A	Cattle dung cake price in local market (Rs/kg)	5-7	5-7	4-5	4-5	-	1.5-2	1.5-2	1.5-2
B	Livestock per HH (excl. calves) [Nos]	0.79	0.82	1.45	1.87	2.9	1.7	1.9	1.5
C	Private trees per HH (nos)	3.63	0.71	26.2	56.1	3.2	5.2	4.5	35.73
D	Access to forests/ wastelands (Yes/ No)	No	No	Yes	Yes	No	No	Yes	No
E	% of HHs which use LPG as primary cooking energy	32%	31%	10%	17%	67%	19%	10%	5%
Source: Author's own field surveys									

Agricultural contracts of household (hh): This variable captures the interactions between rich households (large farms) and poor households (agricultural laborers). These interactions also lead to barter trade of energy commodities between households where, for instance, poor households work in the farms of rich households and get crop residues or dung cakes or wood residues as labor wage or as bonus over labor wage. In the field research, household females were observed to be majorly involved in off-farm agricultural labor as they have lesser wage compared to males. The number of females (between 15 to 59 years of age) per household has therefore been used as a proxy to this variable. Within 95% confidence interval, results of logit model 1 indicates that with every increase of 1 household female in the family, the probability of household using modern cooking energy as primary cooking energy decreases by 0.20%, while keeping all other variables constant. One of the reasons could be that with more agricultural labour contracts, household females get greater interaction with large farms who discard their agricultural residues and these females collect them and this surplus crop residues demotivate this household to cash purchase modern LPG gas. Secondly, since they are not paid in cash but in bio-energy residues, they don't have sufficient cash to buy modern energies. While zoib model 1 also suggests negative correlation, but the results are not significant. The results of logit model 2 does not suggests any significant correlation, as household males might have more say in the selection of modern lighting energy who have more association with the markets and have more exposure to market developments.

Household's (HH's) possession of LPG stove through government PDS (public distribution scheme): Under this PDS scheme, government provides subsidized LPG to households. However, to get this connection, household is required to pay a high initial connection fees of Rs 4500. Whereas, households who don't have LPG connection under the government PDS scheme, must buy LPG from black market at almost double price as compared to PDS price. Therefore, the households who possess LPG stove from government PDS scheme are expected to use LPG as primary cooking fuel compared to other households who may only use it as secondary fuel or don't use it at all. The same hypothesis is assessed in the model. This variable is not included in logit model 2 (modern lighting energy transition) as its little correlation is expected with dependent variable. Within 95% confidence interval, results of both logit model 1 and zoib model 1 indicate the significant positive correlation. The marginal effects in logit model 1 indicate that the connection to PDS scheme increases the probability of household using modern cooking energy as primary cooking energy by 20.45%, while holding all other variables constant. Marginal effects in zoib model indicates that when household is not using 100% modern cooking energy, then the connection to PDS scheme is associated with 2.83% increase in the proportion of household's modern cooking energy usage in its total cooking energy usage, while holding all other variables constant. The major barriers which block the households from getting government LPG stove connection are: high connection cost (Rs 4500 per connection), distance from gas distribution agencies and the associated transportation costs of gas cylinders.

Occurrence of Respiratory or eye diseases in the household (hh): The usage of traditional bio-energy for cooking and kerosene for lighting cause indoor pollution which further causes Tuberculosis, other respiratory or eye related diseases amongst household members. During the household surveys, households were asked if they have any of such diseases. However, it was observed that household confirms any such diseases only when diagnosed by doctors and if there is no diagnosis, they take any disease very lightly and don't talk about it. Moreover, it was observed that they generally go to doctors at a very advanced stage of disease as medical services are very expensive. So, it may also happen that household females or males may be suffering from such health problems, but they don't know about it and that's why they did not reveal the same during the surveys. This question in the survey was crucial as it could help in understanding whether respiratory and eye related health problems in the household motivate household to shift to non-polluting energy sources or not. This is a categorical variable which takes the value "1" if any of the household member suffer from Tuberculosis, other respiratory or eye related diseases, and it takes the value "0" otherwise. Results of both logit models and zoib model don't indicate any significant correlation between household health and choice of energy source. The reasons could be that households are unaware of the harmful impacts of the indoor pollution caused by traditional bio-energy or kerosene, and there are also local perceptions that food cooked in traditional bio-energy is tasty and good for health as discussed in chapter 2. Further locals also believed that smoke caused by traditional bioenergy drive away the mosquitos from the home. So, this local perception neglects the harmful impacts of traditional bio-energy base cooking. In the surveys, there were 36 households which mentioned about the above health problems amongst their females, whereas only 2 households confirmed the above problems amongst household males. So, these problems were more amongst household females. It may happen that household heads (decision makers) who are generally males, are not aware of the harmful impacts of traditional cooking on females or even if they are aware, they are not much bothered about the female health in the household. Thirdly, as every household receives 3 liters of subsidized kerosene from the government, it demotivates them to shift to modern lighting energies.

Years of education of household's (hh's) highest educated member: This is the highest number of years of education of any of the household member. If the highest education in the household is 10^{th} pass, then this takes the value of 10 and likewise. This variable is only included in logit model 2. Due to its high correlation with high female education of household and household head's education year, this variable is not included in logit model 1 and zoib model 1. The results of logit model 2 does not indicate any significance with household's transition to modern lighting. The reason could be the widespread stealing of grid electricity and provision of highly subsidized kerosene to households. Although grid electricity supply is highly erratic, but households expect that the government will eventually improve its power supply. Moreover, during examination time of children, government anyway gives improved grid supply to rural areas so that the examination results of its control area improve. Because of the above reasons, even educated households are not motivated to look for better alternatives of lighting.

Presence of young women in household (hh): This variable is the number of household's female youths in the age bracket of 15 to 34 years. This variable is only included in logit model 2, but not in logit model 1 and zoib model 1. It is expected that with more number of young females, household will be more concerned about their safety and will use improved and reliable lighting for the household. For example, when these ladies go to toilet outside their house in early morning or late evening, they can carry solar lamps with them which are more reliable unlike kerosene lamps which can be extinguished by wind. Also, young females spend more time within the household and therefore they are more bothered about the lighting. The same behavior is tested in the model. However, the results of logit model 2 does not indicate its significant correlation with the household's transition to modern lighting. Easy opportunities of stealing grid electricity (although highly erratic and unreliable), false promises of local politicians of strengthening local grid electricity supply, along with the provision of highly subsidized kerosene, demotivates household to make any investments into reliable modern and clean lighting energy technologies.

***Household distance from kerosene PDS shop*:** To provide subsidized grains, sugar, kerosene etc. to rural households, government set up PDS (Public distribution system) shops in rural areas. This shop generally caters to a cluster of villages or a big village. It is expected that the household which are closer to PDS shop gets subsidized kerosene very easily and sometimes in comparatively more quantity (with good relationship with PDS shop owner). This may demotivate such household to invest in any modern lighting technology and the same behavior is tested in the model. Please note that LPG gas (under PDS scheme) is not distributed by these shops. This variable is not included in logit model 1 and zoib model 1. Results of logit model 2 does not shows any significant correlation. The reason could be that the villages which are away from PDS shops are also remote in nature and grid electricity stealing could be more widespread there. Secondly, it was observed in field research that even distantly located households (from PDS shops) were able to get around 2 liters kerosene per month from PDS shop. In a field experiment (carried out during the field research), this amount was observed to be sufficient for running 1 lamp for around 4-5 hours each day for a month. So, when used judiciously, this amount could meet basic lighting need of the household.

Caste of the village chief of the household: This is a categorical variable and it takes value "1" if the village chief of the concerned household is from upper caste and it takes value of "0" otherwise. This is only used in logit model 2. Results of logit model 2 indicates that within 90% confidence interval, upper caste village chief of the household has positive influence on household's utilization of modern lighting energy. Marginal effects in logit model indicate that, within 90% confidence interval, if the village chief of the household is from upper caste, then it increases the probability of household using modern lighting by 7.09% while keeping all other variables constant. The reason could be as follows. During the field research, it was observed that upper caste village chief had a significant clout in the village, so they were able to unite villagers more effectively and as a result they had more influence in the local government departments and were more successful in bringing government modern lighting schemes to their villages. These schemes could be free solar lights for Below Poverty line (BPL) households, free solar street lights for the village, etc. Whereas villages with lower caste chiefs might have to deal with more internal politics due to jealousies from upper caste households and this results in failure to bring good government schemes to the village.

3.5 Conclusions and Recommendations

Field research as well as government surveys indicate that majority of Uttar Pradesh's (UP's) rural population remain dependent on traditional and polluting household energy technologies. Previous studies have analyzed the determinants of household's energy transition by emphasizing on consumer utility maximizing behavior of the household. However, rural households are not just the energy consumers but also the producers of energy. This study analyzed household's activities and their interactions to identify the factors impacting household energy transition. For this analysis, study applied econometric techniques such as ZOIB (Zero One Inflated Beta regression) and Logit regression on the household survey data from UP. This section summarizes the major research findings and suggests recommendations which can facilitate households' modern energy transition in UP.

Water-Energy-Food production nexus (WEF nexus) and its impact on household's modern energy transition

The results of the analysis indicate that household's agricultural production has an impact on its cooking and lighting energy choice. For instance, results showed that larger cattle endowment encourage household to consume larger quantity of traditional bioenergy (cattle dung cakes) in its cooking energy mix. The results also showed that regular non-agricultural income of household's male member increases the probability of household's modern cooking energy and modern lighting transition by 8.6% and 13.6%, respectively. Larger labor endowment (household size) was also observed to be negatively associated with household's transition to modern cooking and lighting energy. Further results also indicated that the large off farm agricultural contracts of the household discourage the household to use modern cooking energy as its primary cooking fuel and encourage the household to use larger amount of traditional bio-energy in its cooking energy mix. The unpredictabilities and the irregular incomes associated with the agricultural production, the surpluses of agricultural labor and agricultural biproducts (such as dung or crop residues) and lack of awareness on modern energies (such as biogas) are some of the reasons for this household's behavior. To overcome these challenges, it is required to create synergies between household's agricultural production and its modern energy utilization. This can be done by identifying suitable energy systems that utilize local energy resources for modern energy production (decentralized energy systems) and creating value for the local households to participate in such energy systems both as energy feedstock supplier as well as final energy consumer. Further, it also requires robust business model that makes the operation of such energy enterprise (serving the local households) sustainable while taking care of households' willingness to pay for the energy services. For local households, such arrangement can provide income augmentation, improve their purchasing power for energy as well as decrease their vulnerability to price shocks for food and energy. One such example comes from India where the company "Husk power Systems" sets up biomass gasifiers for power production (mini grids) in rural areas of Bihar. These mini grids purchase rice crop biproducts from households, use them for power generation and sell the electricity back to the households not just for their domestic consumption but also for agricultural production (such as for powering local rice dehusking mills, or pumping irrigation water, etc). This arrangement utilizes agricultural surpluses from the rural households, give them additional income that mitigates their financial challenges to buy modern energies, provide cheap and financially viable energy to the households, and provide training as well as employment to local village youths in operation of the mini grid. This company has set up around 84 such mini grids serving several thousands of people in rural Bihar in less than 4 years from the start of its operations (PWC 2016).

Government policy instruments and household's energy transition

Results showed that government's policy instrument such as household connection to government LPG PDS scheme is associated with 20.5% increased probability of household using modern cooking energy as its primary cooking fuel. However, high connection cost is one of the barriers to avail this LPG PDS scheme. Secondly, getting an LPG connection also involves significant efforts (administrative difficulties) and bribery. All this demotivates marginalized section of the rural households from taking the LPG PDS scheme connection and using LPG as their primary cooking energy source. So, government's policy instruments could have positive impacts, but they should be strengthened in a way that even the most backward and marginalized section of the rural households can avail benefit from them. Waiving off the initial LPG connection cost, opening LPG gas agencies in remote areas, easing the process of LPG connection are some of the solutions that can be explored. Results also showed that household's proximity to markets is another important factor that affects household's transition to modern energies. This is because the households living close to the markets have comparatively higher opportunity cost of time and this demotivates them from spending time on bioenergy collection. Also, proximity to markets brings proximity to market information on different technologies, which enables households to shift to modern energies. This calls for the efforts to bring marginalized communities towards the center of development and connecting them to the main stream. Government's investment on infrastructure such as roads, employment schemes, developing education & entrepreneurial skills, etc are expected to be fruitful in this regard.

Institutions and household's energy transition

The results also indicated that the local institutions such as barter trade between households (for labor and bio-energy) and local bioenergy markets impact the cooking energy utilization of household. For example, households who work in the farms of rich households and receive agricultural residues in return of their work, were observed to be having greater utilization of traditional bio-energy in their total cooking energy mix. Encouraging decentralized modern energy systems can mitigate this phenomenon, where households rich in bio-energy resources (large landlords) can sell their surplus residues to decentralized energy systems, and their money generated can be used to pay cash wage to local agricultural labors (instead of paying them in bio-energy residues). While, this will increase the paying capacity of poor households for energy services, the local sourcing of energy feedstocks will result in cheaper modern energy production thereby benefitting both rich and poor households. Results also indicated that the upper caste of village chief can impact the modern lighting transition of the village households, which is perhaps due to his/ her capability to unite locals and bring government modern energy programs to his/ her village. This signifies the importance of robust institutional models for the success of modern energy initiatives.

Social factors and household's modern energy transition

Several social factors also impact household's energy transition. For example, results indicated that the higher education of household female has a positive impact on modern cooking energy transition. So, encouragement to female education is an important driver for household's modern energy transition. Local misconceptions related to LPG and biogas and lack of awareness on modern energy technologies pose challenge to the acceptance of modern household energies. Results indicated that the household headed by low educated and old aged decision maker, has higher traditional bio-energy consumption in its total cooking energy mix. Such households therefore have greater tendency to get trapped in such misconceptions. Educational programs should therefore be undertaken in the rural areas to explain households about the harmful impacts of traditional bio-energy and the significance of modern energies.

The findings of this chapter confirm that the rural household's energy choice decisions depend on the complex linkages of its household activities and its interactions with other households. Encouragement to decentralized energy systems supported by strong business and institutional models, along with the community awareness on modern energy use, can help in households' modern energy transition. The following chapter takes the discussions on decentralized energy systems further. Here, an analysis will be made that how a village community choose the best energy solution for their energy demands, considering energy systems interdependencies and linkages with their food security.

CHAPTER 4

4. MODELING AN OPTIMAL VILLAGE ENERGY SYSTEM (VES) CONSIDERING ENERGY SYSTEMS INTERDEPENDENCIES AND LINKAGES WITH FOOD SECURITY

A vast body of literature suggests that the provision of sustainable and affordable modern energy supplies greatly impact the overall development in rural areas (Kaygusuz 2011, Ghosh et al. 2004, Sovacool, 2012a). Strengthening rural energy supply is therefore necessary for India's rural development. However, India faces an enormous rural energy poverty challenge, with a majority of its rural population lacking access to electricity (Harish et al. 2014) and dependent on traditional biomass for thermal applications (Rehman et al. 2012). The field research in rural Uttar Pradesh during year 2015 (as discussed in Chapter 2) observed the similar energy situation in this region, where around 80% of the surveyed households were dependent on traditional bioenergy as their primary cooking energy source, while only 50% of the surveyed households had electricity grid connection. One of the major reasons for the continued energy poverty in rural India is the government's constant reliance on centralized energy planning which gives more emphasis to the load and industrial centers such as cities while rural areas are often ignored. Several studies have advocated decentralized energy as a solution for eradicating energy poverty in rural India (Hiremath et al. 2010). Moreover, with significant bio-energy and solar potential, renewable energy should be an important component of decentralized energy planning in rural India. However, there exist several challenges in the decentralized energy system planning, such as: 1) wide variety of energy technologies with varied characteristics and efficiencies, 2) financial analysis difficulties, 3) constraints in terms of interdependencies between energy utilization and food security as discussed in the introduction chapter, 4) constraints in terms of cultural barriers. Thus, it is very important to find suitable decentralized energy system's planning strategies, and the same is the objective of this research. Section 4.1 below present the literature review on the strategies of modeling decentralized energy systems (DES) and their shortcomings. The research gap identified in the literature review leads to the conceptual framework that guides this research work, and the same is discussed in section 4.2. Section 4.3 presents the mathematical representation of model which has been developed to identify an optimal village energy system considering energy system's inter-dependences and linkages with food security. Section 4.4 discusses the results of the model in different scenarios. Section 4.5 concludes this chapter and provides recommendations that can aid in the widespread of decentralized energy systems.

4.1 Literature Review: Existing strategies for modeling decentralized energy systems (DES)

For an appropriate decentralized energy planning, community-based energy system could be a better approach compared to that for a single household (HH). This is because that there exist several modern energy technologies such as biomass gasifiers which have great potential in biomass rich rural India (PWC 2016, Palit et al. 2013) particularly in Uttar Pradesh (University of Allahabad 2015), but such technologies need a minimum plant load factor for its technical as well as financial viability (Palit et al. 2013) and are therefore viable only for HH cluster. The same applies for diesel gensets or biogas-based power systems. Therefore, decentralized energy systems (DES) for individual households may miss out such important energy options. However, there also exists several institutional challenges with such community-based DES. Palit and Sarangi 2014 argues that if community-based approach can be combined with an entrepreneurship model, then the decentralized energy system for a village cluster has a great potential in rural India. There exists significant literature on the modeling of decentralized energy systems, where the following 2 strategies have been majorly applied:

- Studies that utilize off-the-shelf softwares for modeling hybrid energy system such as HOMER, RETSCREEN, MARKAL, LEAP etc;
- Studies that utilize their own customized optimization models

In addition to optimization, there are also studies that use GIS (geographical information system) for DES planning, but they give more emphasis to stability of resource supply (Nakata et al. 2011).

The section below presents the existing literature on both above-mentioned strategies and simultaneously highlight their shortcomings.

4.1.1 Application of "off-the-shelf" hybrid energy system modeling softwares

In this category, HOMER (Hybrid Optimization Model for Electric Renewables) developed by NREL (National Renewable Energy Laboratory) and RETScreen developed by Natural Resource Canada are the two most widely used softwares/ models (Salehin et al. 2016, Akella et al. 2007). For a given energy demand, HOMER simulates optimized decentralized energy system using given set of energy technologies and compares costing of different electrification options (Akella et al. 2007). RETSCreen is an excel based software that analyze different scenarios for the energy system and provides detailed financial cost analysis for the same (Salehin et al. 2016). There exists rich literature on their application. Sen and Bhattacharya 2014 utilize HOMER to propose the least cost hybrid electricity generation system to satisfy the electrical needs of an offgrid remote village Palari in Chhattisgarh, India. In doing so, it considers four renewable resources such as small hydropower, solar PV, wind turbines and bio-diesel generators. It resulted in a least-cost combination of power technologies meeting demand at a cost of $0.42/kWh, with solar, biodiesel and small hydro contributing 14%, 10% and 76% respectively to the energy mix. Kobayakawa and Kandpal 2014 is another HOMER based study that designs a hybrid electricity system for a village in West Bengal, India whose levelized generation cost matches with the village households' willingness to pay for electricity services. HOMER has also been used in other parts of the world. For instance, in the setting of Sri Lanka, Givler and Lilienthal 2005 utilized HOMER to compare the cost benefits of PV- diesel hybrid system viz-a-viz stand-alone small solar home systems (which consists of small sized panel along with a battery). Giatrakos et al. 2009, Karakoulidis et al. 2011 are few more such examples. For the studies applying HOMER for DES modeling, Sen and Bhattacharya 2014 argues that most of the hybrid options use a limited set of technologies, mostly renewable power technologies. Moreover, it argues that most HOMER based studies concentrate on domestic electricity supply and do not consider the agricultural, irrigation and commercial electricity demands for the socio-economic development of the whole region. Lately, HOMER has also added the feature of thermal energy system modeling, but the possible thermal energy conversion technologies are limited with major emphasis on household air heating.

RETScreen is another popular software that has been significantly used for analyzing different energy system scenarios. For instance, Adrianus 2012 utilizes RETScreen to analyze the feasibility of replacing diesel-based power system with solar PV plant, for meeting the demand of a selected location in Australia. In the settings of Lebanon, Ahmad 2006 utilizes RETScreen to analyze the financial feasibility of solar thermal collectors as an alternative for water heating. Himri et al. 2009, El-Shimmy 2009 are few such applications of RETScreen.

Sinha and Chandel 2014 makes a review of the existing hybrid energy system modeling software. The study observed that only 3 out of their 19 surveyed models were capable of modeling thermal energy system and only 3 were capable of inputting bioenergy as a potential energy supply option, while all were capable of modelling electricity systems with emphasis on solar, wind, hydro, battery storage and diesel technologies.

While HOMER and RETScreen are majorly used for the energy planning at local level, the other modeling software such as MARKAL, TIMES, LEAP, EnergyPLAN are majorly used at regional and national scales. For instance, Pina et al. 2013 applies EnergyPLAN and TIMES model for analyzing evolution pathways for Portuguese energy system with high renewable penetration. There exist examples of application of LEAP software at local scales, however, it is mainly used for the building of energy supply and demand scenarios considering the socio-economic factors such as economic growth, population growth etc. For instance, Mustonen 2010 utilizes LEAP in analyzing energy consumption scenarios of a Laos's village where it studies that how different village energy services contribute to the achievement of the UNDP's millennium development goals. Limmeechokchai and

Chawana 2005 is a similar study conducted in the setting of the rural setting of Thailand. Lately, LEAP has integrated an energy system optimization module in its software, which can be used for designing the optimum decentralized energy system, however, the power system and thermal energy system optimization is not interlinked and must be implemented separately. This would be undesirable for DES's modeling in rural areas where an energy resource, for instance crop residue, can be used for both thermal and power applications in the village. In a reply to author's question, the developers of LEAP software confirmed this limited modelling capability of LEAP software.

4.1.2 Application of customized optimization models for modeling the DESs

In this approach, energy system is modeled in a way that the expected outcome from the energy system (such as least energy system cost) forms the objective function of the model, whereas the behavioral aspects of the system (such as biomass energy availability, energy supply, energy demand, cultural aspects) form the constraints of the model. Then, different optimization techniques are used to find the energy supply options that fulfil the objective function. The existing literature utilizes the following optimization techniques:

Single Objective Linear optimization (LP) technique has been widely used in the optimization of decentralized energy solution systems. For instance, Patil et al. 2010 utilizes linear optimization model to develop an integrated renewable energy system for a village cluster in Uttarakhand, India. It uses minimization of system cost as the objective function. Assuming the entire cooking energy demand in the village being met by biogas, the study assumes that the remaining dung availability in the cluster can be utilized for power production. Further, assuming the total crop & forest residues availability for power production and the opportunities of energy plantation on waste lands, it finds an optimal energy supply mix for meeting the cluster's energy demand. The study has several shortcomings. Firstly, the energy system modeling restricted itself to the cluster's power supply while assuming biogas to be meeting cluster's cooking energy demand. This is not a practical approach because the same energy feedstocks can be used for thermal as well as power systems. For instance, there could have been a case where crop residue combusted in modern improved cookstove might have been the most viable cooking energy system, whereas biogas might have been the most viable power or irrigation supply option. However, the study missed exploring such options. Secondly, the study did not consider the energy-food nexus linkages. For instance, the study assumed the total dung production in cluster to be available for energy production, however it missed to analyze its repercussions on the fertilizer requirement of the cluster. Similarly, it assumed total waste land availability for energy plantation, however, these waste lands may also be important grazing grounds for the livestocks. Similarly, the study assumed the total crop residues to be available for energy production, ignoring its utilization for livestock feed.

Herran and Nakata 2012 is another such study from Colombia that applies a linear optimization model to design a regional decentralized electricity system using agricultural and forest residues, while considering rural-urban energy consumption disparities. Here, system's performance is evaluated based on net system's cost, households' income generation from biomass sale and the CO2 emissions. The model assumes that all agricultural residues are available for energy purposes as an alternative for waste disposal, while assuming ban on their combustion in open fires. The study concluded that by displacing diesel power with bio-energy based power generation, reduces the electricity costs while augmenting the local incomes, both these factors resulting in improved electricity access in remote areas. However, the study has several shortcomings. For instance, the study assumes that all agricultural wastes are used for energy purposes as an alternative for waste disposal. Whereas, some agricultural wastes such as rice crop residues and sugarcane green leaves which are discarded by rich farms, are used by poor farms for livestock feed, and forms an important food-energy linkage. Secondly, the agricultural wastes considered in the study include rice husk, sugarcane residues, wood etc. are also used as cooking fuels, and there exists strategies (like improved cookstoves) which provides cleaner cooking energy alternatives with such residues, and therefore opportunities of using such residues for cooking energy cannot be ignored.

Chauhan and Saini 2016 utilize linear optimization model to simulate an electricity system for a cluster of villages in Uttarakhand, with the objective of low energy system cost. The model utilized only few selected energy technologies and did not consider any implications on the WEF nexus around the energy use of communities. Akella et al. 2007 is yet another example of the application of linear optimization technique for DES for a village cluster in Uttarakhand province of India, but the focus is only on electricity system. In context of developed countries, Nakata et al. 2005 uses linear optimization modeling to study low cost opportunity to integrate renewable energy systems (wind, photovoltaic, and biomass) to provide electricity and heat in rural Japan. However, the study restricted to wind, solar, biomass and grid, while for meeting heat demand, it restricted itself to geothermal heat pump, petrol heat and LPG heat. However, as discussed before, there could be competition between thermal and power system for the utilization of bio-energy.

<u>Multi objective Linear optimization</u>: Most of the linear programming models discussed above have a single objective function such as minimizing the total cost of the energy system. Optimizing an energy system may involve multiple objectives namely minimizing the cost, maximizing use of local energy sources, maximizing employment, reducing emission of pollutants, etc. Multi objective linear optimization caters to such challenges. Deshmukh and Deshmukh 2009 is one such study that optimize

an energy system for the selected rural cluster in North Rajasthan, considering their lighting, electricity, cooking and pumping needs. It uses several objective functions which include minimizing total system cost, minimizing total harmful emissions, minimizing usage of petroleum products, while maximizing system efficiency and reliability. On the energy supply side, it considers bioenergy, LPG and solar thermal as the available energy resources. The study found that biomass electricity should be promoted for lighting, electricity and pumping applications, while biomass, biogas, LPG and solar thermal for cooking applications. It also recommended that mix of 2 villages for micro level energy planning results in better optimization of available energy sources. However, this study had the following shortcomings. Firstly, study restricted itself to few selected energy conversion technologies while modeling the energy system. It did not even consider solar PV as a potential electricity solution whereas it considered solar thermal for cooking energy. Secondly, but very importantly, while modeling the available bioenergy resources for end use energy application, it did not consider the food-energy nexus linkages of these resources. For instance, it assumed that 75% of the produced cattle dung can be used for energy production because it argues that around 25% of dung is being used for dung cake production, whereas it did not consider the usage of dung as fertilizers in the field. Similarly, while modeling other bioenergy resources such as crop residues for energy production, it did not consider the nexus linkages for crop residues for instance with livestock feed.

Hiremath et al. 2010 is yet another study. This research is done in the settings of Tumkur district of India. It utilizes similar objective functions as used by Deshmukh and Deshmukh 2009. However, still it restricts biogas for cooking, and crop & wood residues for power. However, the combustion of wood, dung cake and crop residues could also provide modern cooking energy options. Secondly, this study also failed to capture the interdependency that exist between dung-based energy and dung-based manure as it considered 50 % of the available cattle dung for biogas and remaining 50% for dung cake. Similarly, no livestock feed- energy interdependency was accounted for crop residues, as it allows entire available residues (from irrigated and non-irrigated lands) to be available for energy production.

Rabbani et al. 2014 and Kazemi and Rabbani 2013 are 2 recent studies that have also incorporated demand side management (DSM) as one of the objective functions in analyzing the optimal decentralized energy system. Their findings suggested that DSM measures can also contribute in improving the financial viability of the DESs. However, studies focused only on the electrical systems and 4 renewable energy supply option such as Solar PV, Wind, Geothermal and Hydro. Kanniapan and Ramachandran 2000, Chetty and Subramanian 1988 are few other examples of multi objective linear programing, but here also the focus is only on electricity system.

In addition, there also few examples of non-linear programming (El-Zeftawy 1991, Ashok 2007) and Mixed Integer Linear programming model (Rabbani et al. 2014 and Kazemi and Rabbani 2013), which are generally used when the optimization problem is to determine on/off scheduling of units in power system operation (Shahrakht and Kazemi 2013) and for the non-linear renewable energy such as wind power.

4.1.3 Summary of the shortcomings in the above discussed literature

Most of the available "off-the-shelf" hybrid energy system modeling softwares are only capable of modeling decentralized electricity systems with emphasis on solar, wind, hydro, battery storage, diesel technologies, while only few can model thermal energy systems and only few are capable of inputting bioenergy supply for modelling the energy systems. However, modeling electricity system in isolation to cooking/ thermal energy or pumping system is not a good approach for rural India (rich in bio-energy) because bio-energy feedstocks such as crop residues, dung etc. can be used in power as well as in thermal and pumping systems. There exists few optimization software such as LEAP, which can also model optimized thermal energy systems for decentralized applications, however, the optimization of thermal and power electricity systems is not interlinked. The other optimization software such as MARKAL which can optimize both thermal and power systems, are generally used in large and regional scales with very limited examples of applications for local scale. There exist several studies which have developed their own customized single and multiple objective linear optimization models for decentralized energy systems. However, most of them focus on electricity systems. There exist some studies which have developed models analyzing both electricity and thermal energy systems simultaneously, but most of them have restricted themselves to few limited energy sources such as few selected renewable energy resources. This does not allow practical evaluation because potential rural customers keep all the possible options in mind while deciding on the best energy solution, and this does not include just renewable energy systems. Most of the discussed optimization studies also failed to consider linkages between power, thermal and mechanical energy systems, for instance, in terms of common feedstock. Almost all the available literature on decentralized energy planning failed to consider the interlinkages that exist between energy and food security. Most of the discussed studies have focused on estimating fuel consumption, rather than disaggregating services and appliance, for instance in bio-energy based cooking options, there could be opportunities for different types of traditional and modern cook stoves with different efficiencies. Bioenergy such as crop residues are generated by rural households and is therefore an important income source of the household, yet, there are not many studies which have considered this aspect while modelling bio-energy based systems. There is also a very little research on the influence of Demand Side

Management (DSM) measures in improving the viability of decentralized energy system. To fill the above discussed research gaps, this research attempts to develop an optimal village energy model that selects the most optimal village energy system, while considering energy systems interdependencies and its linkages with food security.

4.2 Conceptual Framework

Figure 4.1 presents the conceptual framework utilized in this research, which has 4 major depictions. Firstly, the central green portion shows the interconnection between the energy supply, energy demand and WEF nexus of the households and communities. Here, it enlists all possible energy supply options for the community (including own bioenergy production). Simultaneously, it breaks the energy demand of the community into cooking, lighting, power and irrigation. It then shows that how the same energy supply option (such as crop residues) which can be limited in village, can meet different types of community energy demand through different energy conversion technologies and this creates interdependencies between energy sub systems (eg. cooking, lighting, power etc.). As an example, it shows that the crop residues produced by households can be used for cooking energy (if burnt in traditional/ improved cook stoves), or they can be gasified in biomass gasifiers for electricity generation. One may argue that, cost wise, crop residue as cooking fuel will always win over the crop residue usage for power production, however, there may be a case that crop residue based power production results in a very cheap power production that it replaces a very expensive power production, and this results in an overall low-cost energy system for the village (incl. power, thermal and irrigation energy). Even solar resource may have competition between solar thermal, solar power and solar pumping application, not in terms of solar insolation but the space for erecting solar panels/ tubes. Therefore, decentralized electricity supply for a community cannot be modeled in isolation to decentralized thermal energy system and to its irrigation system. These possible energy supply options, their conversion technologies and the village energy demands, and their interlinkages are further elaborated in Section 4.3.1. Secondly, the energy supply-demand balance also depicts the opportunities of Demand Side Management where communities can divide their energy demands for different types of the day and it may happen that certain technologies provide lower cost of energy generation in certain time of the day. Thirdly, in Chapter-1 of this thesis, it was discussed that the energy related decisions of the households/ group of households (communities) are interconnected with their food production and water utilization decisions. The central-left green portion of the conceptual framework below shows such linkages between energy (supply& demand) system and WEF Nexus around the households' energy use. For example, it shows that while developing an energy system for the community, an energy planner cannot just assume that the entire cattle dung produced in the village can be used for energy production because cattle dung is also an important fertilizer for the farm, or vice versa. Similarly, planner cannot just assume that the entire crop residues produced in the village can be used for energy production, because crop residues such as rice straw, wheat straw, millet straw, Sugarcane top etc are also important livestock feed in rural areas, while they can also be used for energy production. Given the fact that the average land endowment is decreasing in India, farmers are growing little green fodder crops for livestocks and they are now increasingly becoming dependent on agricultural residues for livestock feed. During this field research in Uttar Pradesh, farmers were even observed to be feeding rice straw to their livestock, despite of the fact that rice straw is acidic in nature and affects the yield and health of the livestock. Similarly, firewood competes for land that can be used as grazing land or for growing food. Even solar technology needs land for erecting solar plates and competes for land which can be used for food production. Therefore, energy system for a community cannot be modeled in isolation to its food production and water utilization. Section 4.3.1 and 4.3.2b elaborates the interlinkages between energy systems and the WEF Nexus that has been considered under this research. Finally, the blue and grey portions of the conceptual framework show that there could be several external factors (Scenarios), for instance, efficiency improvement in new energy technologies, or some subsidy program on renewable energy or say carbon tax on fossil based technologies or some local misconceptions about energy technologies etc., which can affect households use of natural resources, their food production, energy production and consumption. This impact of external drivers on the WEF nexus around households' energy use can result in potential tradeoffs and synergies, with their impacts on food security, poverty reduction, environmental sustainability, labor market, gender equality, health and education. For example, this can result in cost effective energy system which improves the energy access situation of the households, or this can result in saving of the cattle dung for agricultural fertilizers impacting the food production of the household, or this can result in saving of time from bioenergy calculation which household woman can now utilize for better education, etc. These outcomes can again impact the influence of external drivers on the WEF Nexus around households' energy use. For instance, better education can lead to behavioral changes amongst the communities and this can influence the adoption of new energy technologies by the communities again potentially impacting the WEF Nexus.

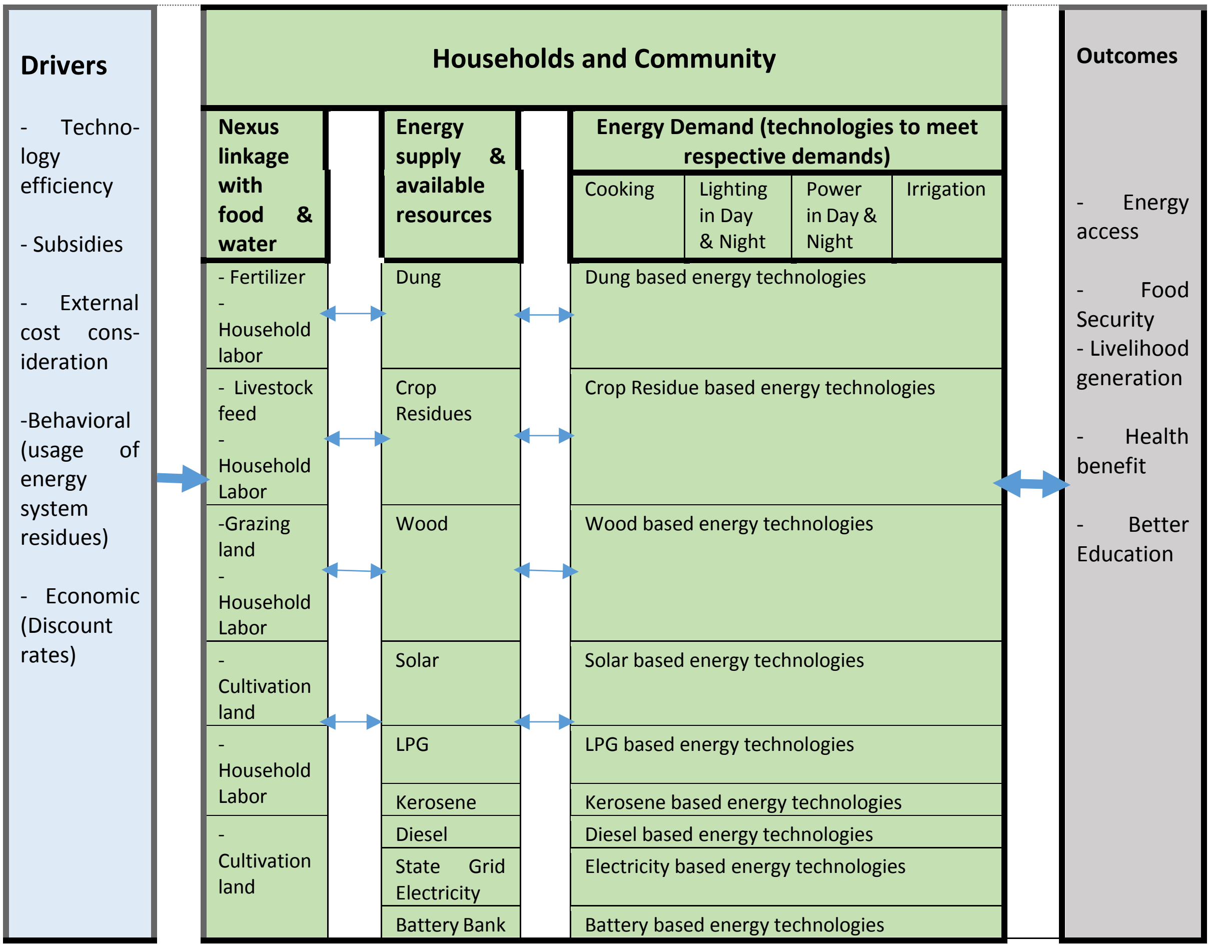

Figure 4.1: Conceptual Framework guiding the research on optimal village energy system
Source: Author’s own depiction (with inputs from Mirzabaev et al. 2015)

4.3 Description of the Village Energy model

4.3.1 Energy systems interdependencies and linkages with food security

Extending the discussions of conceptual framework, table 4.1 presents the possible energy sources which can be applied for decentralized energy systems in this research, their possible energy conversion technologies, their end use applications to serve different types of energy demands and their linkages to the WEF nexus. For assessing the opportunities of demand side management, energy demand of the village (power & lighting demand) is divided for day time and night time. Here in table 4.1, column B presents the different energy resources considered in the study. The selected list includes those energy resources which are already being used in the surveyed villages, or whose potential exist in the villages. The list does not include resources like wind, hydro because their potential does not exist in the surveyed villages or in case of wind it needs long term technical assessment to understand its potential which was out of scope for this study. Moreover, experts also argue that opportunities with small sized wind turbines reduces when there are lot of hindrances for instance buildings in the village. In addition, energy sources such as coal and natural gas have limited relevance for decentralized energy applications and are not included in the study. However central grid managed by the government is included.

Column C to H in table 4.1, presents different energy conversion technologies that can transform above discussed energy sources into useful forms of energy for meeting cooking, lighting, electricity and irrigation demands of the community. For instance, it shows that cattle dung can be utilized for meeting cooking energy demand through its combustion in traditional or improved cook stoves, or through biogas produced in digesters. At the same time, it can also be used for meeting lighting needs through biogas mantle lamps, or for power generation by burning biogas in gas engines. Similarly, it maps energy conversion technologies for other energy sources to meet different types of village energy demands. It is to be noted that electric cookstoves and solar thermal based cooking are not considered in the study, because during the field surveys it was observed that households prefer to cook their food in flame because chapatti (Indian Bread) is cooked better and easier in flames. Further, usage of wood in biomass gasifier has not been included in this model as most of the existing case studies in India (for example Husk Power Systems) employ crop residue-based feedstock and therefore most of the operational details of this technology are based on crop residues, and the same has been used in this research.

Interdependencies between energy system and food security are represented in column A. In this research, the energy-food linkage has been considered for cattle dung usage as farm fertilizer, crop residue usage for livestock feed, bioenergy usage with household labor which is included in the cost of bioenergy sold by household to village energy system. However, energy system linkage with cultivable and grazing land has not been considered in the research because of the lack of detailed data on the same. Section 4.3.2 elaborates the demand of local energy sources such as dung or crop residues in non-energy sectors which is crucial for the food production of the village communities. The labor utilized in bioenergy production by communities is captured by the local prices of such commodities and their opportunities of sale to village energy system.

Table 4.1: Energy Systems interdependencies and linkages with WEF Nexus

A	B	C	D	E	F	G	H
Nexus linkage	**Energy Resources**	**Cooking Energy**	**Lighting in day**	**Lighting in Night**	**Power in day**	**Power in night**	**Irrigation energy**
-Farm fertilizer - Labor for collection	**Dung**	- Traditional Cook-stove -Improved Cook-stove - Biogas	Mantle		Biogas based Generators		Biogas based Engines
- Livestock feed - Labor for collection	**Crop Residues**	- Traditional Cook-stove -Improved Cook-stove	Gasifier + Gas Generators				Gasifier based engine
- Grazing Lands for animals - Labor for collection	**Wood Residues (Wastelands)**	- Traditional Cook-stove -Improved Cook-stove	Gasifier + Gas Generators (not included in study)				Gasifier based engine (not included in study)
- Cultivable land (not included in study)	**Solar**	Solar thermal (not included in study)	Solar PV (photovoltaic) with LED bulb		Solar PV		Solar PV with pump
- Labor for bio-energy collection	**LPG**	LPG stove	LPG mantle		N/A	N/A	N/A
	Kerosene	Kerosene stove (not included in study)	Kerosene lamp		N/A	N/A	N/A
- Cultivable land (not included in study)	**Diesel**	N/A	Diesel Genset				Diesel Engine
	State Grid Electricity	Electric Stove (not included in study)	Electricity				Tubewell (Electric Motor)
	Battery Bank	Electric Stove (not included in study)	Battery back up to grid electricity or solar PV				Electric Motor (not included in study)

Source: Author's own depiction

4.3.2 Village energy demand and Bio-energy resources available in village

a. Elaborating the energy demand of the village community

The energy system considered in this study caters to the following energy demands of the village:

- Cooking energy demand (for households, local schools and institutions)
- Lighting demand in day time and night time separately (for households, schools, enterprises and institutions),
- Power demand in day time and night time separately (for households, schools, enterprises such as mills, and institutions),
- Irrigation Energy demand (for local agricultural sector)

Data for this study comes from the 380 household and 8 village surveys in Uttar Pradesh. These surveys were already discussed in Chapter 2 and these 380 households belong to the surveyed villages. These 380 households along with their agricultural practices, and local commercial and institutional units in these 8 villages, will form the village, whose energy system will be modeled in the study. This will be called the village energy system (VES). In the subsequent text, respondent will mean either household or commercial or institutional entity.

- Cooking Energy Demand: The surveys captured the total annual amount of dung cake, firewood, crop residues, kerosene, LPG and biogas used by households, institutions and enterprises on their annual cooking and water boiling needs. This information was multiplied by their respective energy densities of fuels and their respective cook stove efficiencies to gather total useful cooking energy requirement of the village. Since cooking energy demands may vary between seasons, respondents were asked about their cooking energy demands in different seasons, but at the end, the cooking energy was summed to make annual cooking energy demand of village. The same is depicted in figure 4.2.

- Lighting demand: The surveys captured the quantities, power ratings, energy consumption (in case of kerosene, LPG etc.) of lighting devices used by households, local enterprises and local institutions. For instance, using a 14 W CFL bulb consumes 14 Whr of energy with its 1-hour operation. Households were then asked about the daily hours of lighting requirement in different seasons and in different times of the day (day and night are 2-time slices considered in the study). Similar observations were made for local enterprises and institutions such as schools, during the village survey. These results were confirmed with the outcomes of FGDs (with village communities). The communities mentioned that for households' use, they will need around 6 hours of lighting in summers and 8 hours of lighting in winters, mostly during night time. The village chiefs mentioned that for schools they need lighting for 6 hours during day time. The enterprises mentioned that they would need around 2 hours of lighting during evening time. Lighting energy requirement of households, enterprises and institutions were calculated by multiplying the hourly energy consumption of respective lighting equipments with the number of hours of required lighting. Further, since different energy sources have different lumen output, for instance LED light gives 21111 lumen-hours/ MJ consumed compared to 20 lumen-hours/ MJ from kerosene lamp (Evan Mills 2003), annual lighting energy demand was converted into annual lumen-hours demand of lighting. This provides an opportunity to find the most optimized lighting solution based on its price per lumen-hour instead of price per MJ because kerosene might have less price per MJ compared to LED light but has higher price per lumen-hour. Annual lumen-hours of lighting required by village community in day time and night time is given separately in figure 3 below.

- Power demand: The surveys captured the quantity and the power ratings of electricity appliances used by the households. Households were then asked about the daily usage hours of their respective power equipment in different seasons and in different times of the day (day and night are 2 time slices considered in the study). For instance, a household mentioned that during summers, it needs 8 hours of operations of 3 fans each in night time and 2 hours of operation of 2 fans each in day time, whereas in winter it needs no fan, similarly this information was collected for all the electricity appliances in the household. Along with their usage, their tentative respective power consumptions were noted, as written in those appliances or as told by household. This information was then correlated with the findings of the village / FGD surveys on the usage of different electrical appliances by households, enterprises and institutions. This way power requirements of households, enterprises and institutions were calculated for different seasons and for different times of the day (during day and during night). The power consumed was then translated into the MJs of energy consumed based on the energy density of electricity i.e. 3.6 MJ/ KwH (Nahar 2002). Annual power required by village community in day time and night time is given separately in figure 4.2 below.

- Power demand for agro-processing: For this, interviews were conducted with the owners of rice, wheat and oil mills in the surveyed villages. Their energy consumption per Quintal (100 kgs) of wheat, rice and oil milled was calculated along with their incomes and expenses per Quintal (100 kgs) of milling. For assessing the quantity of wheat, rice and oil milled in these mills (coming from local village households), following strategy was adopted. Household surveys captured the information on wheat, rice and oil produced, consumed and sold by the households. However, farmers only mill those quantities which they consume in house. Assuming entire grain amount consumed by surveyed households to be milled, annual service sale of local mills was calculated. Accordingly, total annual energy requirement of mills was calculated. This information is added in the power requirement of village community in day time as such activities take place in the day time only, and is included in Figure 4.2.

- Irrigation Energy Demand: Household surveys captured the number of hours of irrigation given by household to five of its major crops. This included Wheat, Rice, Sugarcane, Potato and Mustard. Further based on household surveys and experts' interviews, required useful energy per hour of irrigation was measured. Since, most of the irrigation needs were observed being met by diesel pump, this calculation was done considering diesel engine operation. This was multiplied with total annual hours of irrigation required per household. The annual energy required for irrigation is depicted in figure 4.2 below.

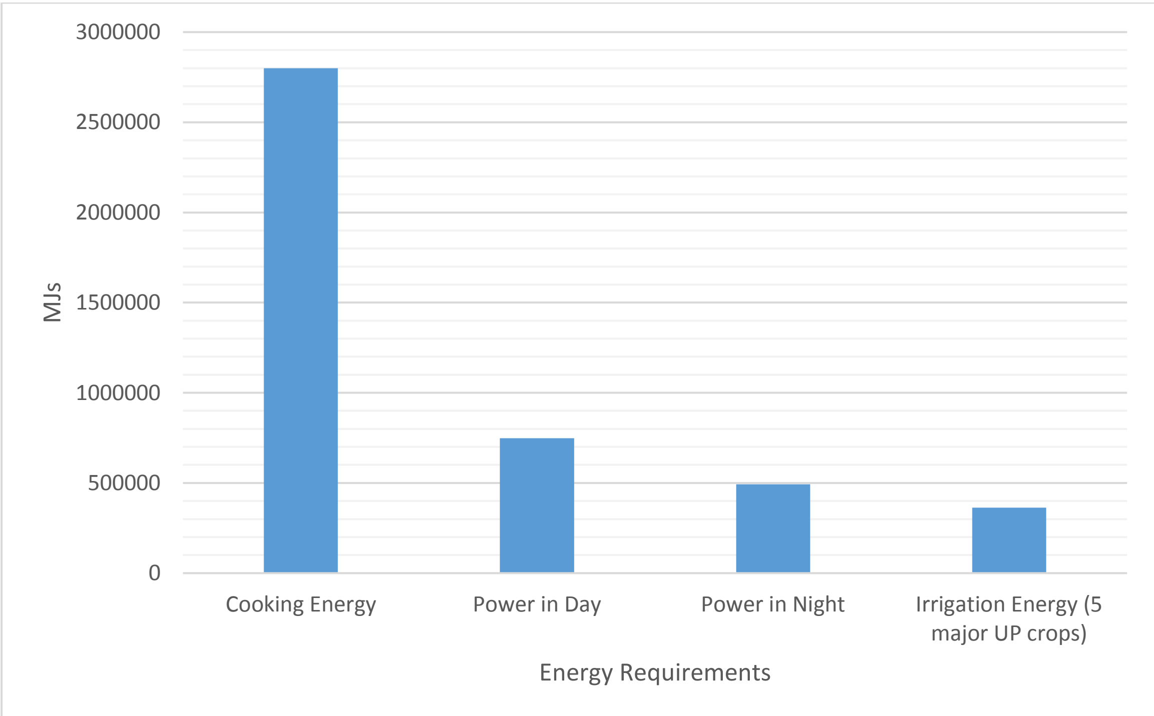

Figure 4.2: Annual Village energy requirements for different applications (except lighting) in MJ
Source: Author's own depiction

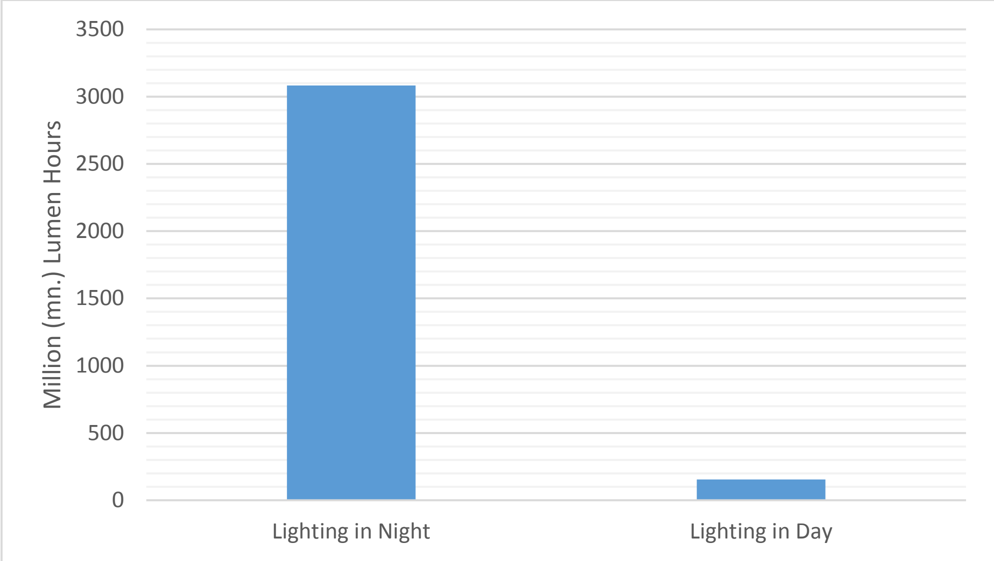

Figure 4.3: Annual lighting requirements of village in million lumen-hours
Source: Author's own depiction

b. Bio-energy supply and food security of the village community

This section elaborates the demand of local energy sources such as dung or crop residues in non-energy sectors which is crucial for the food production of the village communities. The labor utilized in bioenergy production by communities is captured by the local prices of such commodities.

- Demand of animal dung as fertilizer: Household surveys captured household manure (dung based) use of fertilizers for 5 major crops which include Wheat, Rice, Sugarcane, Potato and Mustard. The average values per household were then multiplied by the number of households (380) to form village's requirement.

Table 4.2: Manure requirements of the village

Crops	**Dung based manure requirement of crops in village (Kgs/ year)**
Wheat	382732
Rice	564167
Sugarcane	185705
Mustard	3612
Potato	1030909
Total Manure requirement for village	**2167125**
Source: Author's own field surveys	

- Demand of crop residues as livestock feed: Household surveys captured quantities of different crop residues produced by households and their percentage utilization as livestock feed. Average household values are then multiplied by 380 to form the village requirement. The same is presented in table 4.3 below:

Table 4.3: Crop residues utilization in village (for livestock feed and energy purposes)

Crop Residues	Average mass of residue produced (kg/ HH/ year)	Average residue utilization for livestock (%/ HH)	Average residue available for energy (%/ HH)	Average mass of residues available for energy (kg/ HH /year)
Wheat Straw	2232.956	100%	0%	0
Rice Straw	1215.497	68%	32%	388.959
Rice husk	162.0662	0	100%	162.0662
Sugarcane dry leaves	472.6908	0	100%	472.6908
Sugarcane green leaves (top)	1086.645	100%	0%	0
Crop Residues available for energy per HH per year (kgs/ HH/ year)				**1023.716**
No. of households surveyed				380
Crop Residues available for energy per year for entire village (kgs/ year)				**389012.1**
Source: Author’s own field surveys				

- Bio-energy in the local energy markets: Labor utilization for bioenergy production (collection/ processing) by communities is captured by bio-energy commodity prices in local markets, which can be sold to village energy system. The same is depicted in Table 4.4 below.

Table 4.4: Prices of bio-energy fuels in local markets (average from all surveyed villages)

Bio-Energy fuels	**Average fuel price in local market (Rs/kg)**
Wood	6
Cattle dung cake	2.5
Cattle Dung (Fresh)	0.5
Crop residues (such as rice husk, rice straw, sugarcane dry leaves)	1.5
Source: Author’s own field surveys	

4.3.3 Mathematical Representation of the model

The previous section 4.1 and 4.2 identified research gaps in the modeling of decentralized energy systems for rural areas. To bridge these gaps, this section develops a suitable mathematical model that selects an optimal decentralized energy system for the village fulfilling its cooking, lighting, power and irrigation needs at the lowest possible costs, while considering the energy systems interdependencies & the linkages with WEF Nexus. The model utilizes the linear optimization technique, where the expected outcome of the system forms the objective function, and the system characteristics & the behavior are modeled as constraints. This model is normative in nature where it determines the levels of model variables while optimizing the village community's decision to have the lowest cost of energy system (discounted annual net present value) over the period of analysis. The model assumes that village community has a foresight of 15 years to achieve the overall objective function over the period of analysis under a selected discount rate. The model is static in nature because at the village level, most of the decentralized energy technologies (such as solar mini grids, biomass gasifier) have large life time (10-15 years) and it may not give the flexibility to the village community to make intertemporal decisions. The model assumes that the bioenergy supply comes from within the village (which is the most common practice) and it can-not buy bioenergy from neighboring villages otherwise this Village energy system will also be dependent on other villages. The bio-energy supply is already discussed in section 4.3.2, whereas commercial energy can be purchased from the market. The model is activity-based where the community tries to fulfil its objective (minimization on energy system costs) using several options, under a set of constraints. For example, to meet its energy demand, it can use its own natural resources such as dung, crop residues, wood etc., or it can buy energy supply from the market, under a set of constraints which are described next. Following is the mathematical description of the model. The model is written in GAMS (General Algebraic Modeling System) and is given in Appendix 3.

Objective Function: Rural households in Uttar Pradesh are associated with low incomes and thus low paying capability for energy uses. During the household surveys and the FGDs, their expectation was observed to be an energy system which meets their minimum energy requirements (discussed in the section 4.3.2) at the lowest possible cost. Accordingly, the objective function of the model is to minimize total net annual costs for energy generation (discounted annual net present value) considering 15-year horizon. There were also some concerns on the harmful emissions from traditional use of biofuels. In one energy system scenario, external costs (health damage costs) have been associated with the usage of each fuel and technology and in this way least cost objective function will also consider the health damage costs along with the economic cost with the usage of each fuel. The following equation (1) is the mathematical representation of the objective function.

$$Min(b) = Min \sum_{k}^{6} \left(\sum_{j}^{m} \left(\sum_{i}^{n} X_{\mathrm{ijk}} * Y_{\mathrm{ijk}} \right) \right) \tag{4.1}$$

Where,

b - Net present value of the yearly expenditure on energy system in Rs (for cooking, lighting, power and irrigation demand for village);

k- end use energy application (such as cooking), there are 6 such end use energy applications which include cooking energy demand, lighting demand in day, lighting demand in night, power demand in day, power demand in night, irrigation energy demand;

j- energy source available (such as cattle dung), m= number of such energy sources (column B in table 4.1)

i - energy conversion technology (such as traditional cook stove), n= number of such technologies (column C to H in table 4.1);

X_{ijk} - quantity of useful energy consumed (MJ) of energy resource j (j=1 to m), using energy conversion technology i (i=1 to n), for end use energy application k (k=1 to 6);

Y_{ijk} - levelized cost of energy generation or purchase (Rs/ MJ) using combination of i,j and k. The levelized cost of energy generation (Y_{ijk}) is calculated using equation 4.1a.

$$Y_{ijk} = \frac{\sum_{t}^{T}\left(\frac{I_{ijkt} + M_{ijkt} + F_{ijkt}}{(1+r)^t}\right)}{\sum_{t}^{T}\left(\frac{E_{ijkt}\left(1 - SD_{ijkt}\right)^t}{(1+r)^t}\right)} \qquad (4.1a)$$

Where, I is the investment in energy system; M is the Operations & Management expenses in energy system; F is the Fuel Expenditure in time t on using combination of i,j and k; E is the energy generation by energy system; r is the Discount Rate; SD is the system degradation; T is 15 years (t varies from 1 to 15 years).

Appendix 1 presents the above-mentioned parameters as well as levelized costs of energy generation of all the cooking, lighting, power and irrigation technologies considered for this study.

Demand Constraints

The purpose of these demand constraints is to make sure that there exists a combination of energy resources and their associated energy conversion technologies that fulfils energy demand of the village community. Equation 2 models the cooking energy demand.

$$ced = \sum_{j=1}^{m}(\sum_{i=1}^{n} X_{\mathrm{ij}}) \quad (4.2)$$

Where, ced is the annual cooking energy demand of the village (as discussed in Section 4.3.2); i varies from 1 to 4 (traditional cook-stove=1, improved cook-stove=2, biogas cook-stove=3, LPG cook-stove=4); j varies from 1 to 4 (dung=1, crop residue=2, wood=3, LPG=4); X_{ij} is the useful energy (MJ) provided by energy source j with energy conversion technology i, where the summation fulfils the cooking energy demand for the community.

Similarly, other energy demands are modeled as shown below in Eq 4.3 to 4.7.

$$ledd = \sum_{j=q}^{m}(\sum_{i}^{n} X_{\mathrm{ij}}) \quad (4.3)$$

$$ledn = \sum_{j=q}^{m}(\sum_{i}^{n} X_{\mathrm{ij}}) \quad (4.4)$$

Where, ledd and ledn are annual lighting demand (in million lumen hours) in day time and night time resp. (as discussed in Section 4.3.2); i : 1= dung, 2= crop res, 3= wood, 5= kerosene, 6= solar, 7= diesel, 8=grid, 9= battery ; j : 5= biogas mantle, 6= gasifier with generator based light, 7=kerosene lamp , 7= solar PV light, 8= solar PV light with battery, 9= diesel genset based light, 10= electricity powered light, 11= electricity with battery powered light.

$$pdd = \sum_{j=q}^{m}(\sum_{i}^{n} X_{\mathrm{ij}}) \quad (4.5)$$

$$pdn = \sum_{j=q}^{m}(\sum_{i}^{n} X_{\mathrm{ij}}) \quad (4.6)$$

Where, pdd and pdn are annual power demand in day time & night time resp. (as discussed in Section 4.3.2); i : 1= dung, 2= crop res, 3= wood, 5= kerosene, 6= solar, 7= diesel, 8=grid, 9= battery); j: 12=biogas generator, 13= gasifier based generator, 14= solar pv, 15=solar pv with battery power, 16= diesel generator, 17= electricity grid based power, electricity with battery based power.

$$ied = \sum_{j=q}^{m}(\sum_{i}^{n} X_{\mathrm{ij}}) \quad (4.7)$$

Where, ied is annual irrigation energy demand; i: 6= solar, 7= diesel, 8=grid ; j: 18= solar pv with pump, 19= electricity based tubewell, 20= diesel engine

Resource & other constraints that creates energy systems interdependencies & linkages with food security

These set of constraints are used to: 1) develop interlinkages of utilization of energy sources for different end use energy applications (for instance cattle dung for cooking as well as lighting as well as power generation), 2) create boundaries for the energy system so that the local bioenergy utilization does not encroach upon the food production sphere of communities (for instance crop residue usage for energy does not affect its usage as livestock feed).

Eq (4.8) below shows that the utilization of dung using different energy conversion techniques for different end use applications should not exceed the total amount of cattle dung which is annually available for energy purposes (as discussed in section 4.3.2). However, it is to be noted that if the dung is used for biogas production, then its gives back slurry as the digester output which can be again used as fertilizer. SNV 2011 and IEA undated indicates that the slurry (digester output) has same amount of nutrients as the input dung has, therefore it can also be used as fertilizers in the field. Therefore, while modeling dung in the energy system, the slurry produced, should not be ignored as the potential fertilizer. Equation (4.9) models the amount of slurry produced, in case, dung is used for biogas production. Equation (4.10a) shows that the annual amount of dung used for energy production (de) = total annual amount of dung produced in village (TD) – total amount of dung used for fertilizer whose value depends on the amount of slurry produced (df). Eq 4.10b puts the constraint that total amount of dung used for fertilizer in the village (DF) should be equal to or greater than the sum of df and the amount of slurry produced (S). This way, it can be made sure that utilization of dung for energy production does not influence the dung usage by household for the farm fertilizers.

$$\sum_{k}^{5}(\sum_{j}^{m}(\sum_{i=1}^{1}(((X_{\mathrm{ijk}} * C_{\mathrm{ijk}})/eff_{\mathrm{\ ijk}})/(ED_{\mathrm{ijk}})))) \leq \mathrm{de} \qquad (4.8)$$

Where, de is annual amount of dung (kgs) which is available for energy use; i: 1= dung, & j: 1=traditional cook-stove, 2=improved cook-stove, 3=biogas cook-stove, 5= biogas mantle, 12=biogas power; k: 1=cooking, 2=lighting in day, 3=lighting in night, 4=power in day, 5=power in night; C: Conversion factor from raw fuel to usable form of energy (such as manure to dung cake); this is “3” for dung cake to dung, and “25” for biogas to dung (Field research observations); eff : Efficiency of energy conversion devise. This is given in Appendix table A1.2; ED: Energy density of energy source. This is given in Appendix table A1.2.

$$TS = \sum_{j}^{m}(\sum_{i=1}^{n} X_{\mathrm{ij}} * S_{ij}) \qquad (4.9)$$

Where, TS is total slurry produced by biogas digester (kgs); i: 1= dung, & j: 3=biogas cook-stove, 5= biogas mantle, 12=biogas power; S = Amount of slurry produced per MJ of energy produced (Field Research and SNV 2011).

$$\mathrm{df} + \mathrm{de} = \mathrm{TD} \quad (4.10\ a)$$

$$\mathrm{DF} \geq \mathrm{df} + \mathrm{S} \quad (4.10\ b)$$

Where, df is annual amount of dung used as farm fertilizer that depends on slurry produced (depending on amount of slurry produced, it should suffice for DF); DF is annual amount of dung plus slurry used as fertilizer; de is annual amount of dung used for energy production; TD is total amount of dung produced in the village.

Eq 4.11 shows that the utilization of crop residues using different energy conversion techniques for different end use applications should not exceed the total amount of crop residues which can be annually available for energy purposes without interfering livestock feed (as discussed in section 4.3.2) and is represented by tcr.

$$\sum_{k}^{5}(\sum_{j}^{m}(\sum_{i}^{n}((X_{\mathrm{ijk}}/(eff_{\ \mathrm{ijk}})/(ED_{\mathrm{ijk}})))) \leq tcr \quad (4.11)$$

Where, tcr is annual amount of crop residues available for energy; i: 2= crop residues; j: 1=traditional cook-stove, 2=improved cook-stove, 6=gasifier-based light, 13= gasifier-based power; k: 1=cooking, 2=lighting in day, 3=lighting in night, 4=power in day, 5=power in night,

Equation 4.12 shows that the utilization of wood using different energy conversion techniques for different end use applications should not exceed the total amount of wood which are currently allocated by households for energy purposes.

$$\sum_{k}^{5}(\sum_{j}^{m}(\sum_{i}^{n}((X_{\mathrm{ijk}}/(eff_{\ \mathrm{ijk}})/(ED_{\mathrm{ijk}})))) \leq W \quad (4.12)$$

Where, W is annual amount of wood available to be used for energy; i: 3= wood, & j: 1=traditional cook-stove, 2=improved cook-stove, & k: 1=cooking,

Equation 4.13 models the health damage costs stemming out due to the usage of different energy sources (i) using different energy technologies (j) for different end use applications (k)

$$hc = \sum_{k}^{6}(\sum_{j}^{m}(\sum_{i}^{n}(X_{\mathrm{ijk}} * HC_{\mathrm{ijk}}))) \quad (4.13)$$

where, hc is total health damage costs stemming out of the energy system; HC_{ijk} is health damage costs associated with X_{ijk}. Appendix 1 presents the details on the health costs associated with all possible energy combinations.

Equation 4.14 models the carbon emissions stemming out due to the usage of different energy sources (i) using different energy technologies (j) for different end use applications (k)

$$CE = \sum_{k}^{6}(\sum_{j}^{m}(\sum_{i}^{n}(X_{\mathrm{ijk}} * ce_{\mathrm{ijk}}))) \qquad (4.14)$$

Where, CE is total carbon emissions stemming out of the energy system; ce_{ijk} is carbon emissions (kgs) associated with X_{ijk} (Appendix 1)

Equation 4.15 determines the annual income that the households receive if they sell their bioenergy resources such as dung or crop residues to the village energy system.

$$\sum_{k}^{6}(\sum_{j}^{m}(\sum_{i}^{n}((X_{\mathrm{ijk}} * C_{\mathrm{ijk}}/(eff_{\mathrm{\ ijk}})/(ED_{\mathrm{ijk}})))) * EP_{\mathrm{ijk}} = inc \qquad (4.15)$$

Where, inc is annual household income of all the participating households by the sale of bio-energy resources; EP is the price of energy commodities such as crop residues at which household sell their bioenergy resources to the VES (Field Research); i: 1=dung, 2=crop residues; j: 1=traditional cook-stove, 2=improved cook-stove, 6=gasifier based light, 13= gasifier based power; k: 1=cooking, 2=lighting in day, 3=lighting in night, 4=power in day, 5=power in night.

4.4 Results and discussions

This section discusses the model results. Shadow price of the energy technologies from the model is an important instrument in understanding the energy systems interdependencies. Before discussing the model results, section 4.4.1 explains the concept of shadow price and its significance in optimization problems. In Section 4.4.2, the model results for the entire village energy system in Business-as-usual (BAU) scenario is discussed. In Section 4.4.3, impact of different external factors on the VES will be analyzed. As discussed in the conceptual framework, these factors will be economic (subsidies, discount rates), consideration for health and environment (health damage costs), behavioral (eradicating the misconceptions about biogas slurry), institutional and political (politics around grid electricity). Amongst technical factors, impact of new technologies such as improved cook stoves etc. are already discussed in BAU scenario.

4.4.1 Shadow price from the optimization problem and its significance

In the optimization problem, shadow price of the variable is the instantaneous change in the objective value of the optimum solution per unit change in the variable, given all other data remain the same. For the above discussed village energy model (or for the household model to be discussed in next chapter), this is a very important instrument for understanding the interlinkages between different energy systems of the village/ activities of the household and their interlinkages with village's / household's food security. This can be explained with the case of cattle dung which can be used for cooking system, biogas-based power system or irrigation system, as manure for crop production, and its consumption is also interconnected with the household livelihood as household members spend labor in dung collection/ processing. So, while exploring the possible allocation of dung for let us say power system, the model will also analyze: 1) its monetary impact on other energy systems such as cooking because if limited dung is diverted for power system then household/ community may have to buy a very costly LPG system and this increase the overall cost of VES, 2) the consequences to labor allocation of household because it might be profitable for household to use labor for off farm work rather than spending labor for dung processing for biogas power, 3) the monetary consequences on farm fertilizer because if household diverts dung for biogas power then it may have to purchase expensive fertilizers from market, 4) health damage costs as the case may be. All the above 4 points will associate a shadow price with dung-based power system that how an additional per unit usage of dung based power system will impact the objective value and accordingly model will make the decision. This means that it may happen that the levelized cost of energy generation of a power technology, let's say gasifier power, may be lower then let's say battery power but the shadow price of the former in the model may be higher than latter and model eventually selects latter. In GAMS output, the marginal value of the variable represents the shadow price of the variable. Variables represented by the shadow price of "dot" are the variables which have been chosen by the model for meeting respective energy demands of the village. Variable A with shadow price let's say "- X "will mean that the objective value will decrease by value X per unit increase in the variable A, given all other data remain the same. The sections below will also discuss the shadow prices of different technologies from the model. The following section discusses model results in BAU scenario.

4.4.2 Business-as-usual (BAU) scenario

Business-as-usual Scenario includes existing conditions on the field. Here, village receives usual subsidized grid electricity from state electricity department for domestic, agriculture and commercial use, with limited availability. Appendix 1 presents the electricity prices for the above electricity consumer categories and Village Energy System (VES) falls in commercial category. The bio-energy feedstocks such as dung, wood, residues are priced at local market rates which already captures the labor and material costs for processing these feedstocks. VES buys such feedstocks from local households. The availability and constraints of various bioenergy feedstocks is already discussed in section 4.3.1 and 4.3.2. Although, subsidies on some renewable energies exist, they don't reach to rural communities easily, and therefore no renewable energy subsidies are considered in this scenario. Model selects lighting technologies based on their lighting cost per million lumen hours, as discussed in section 4.3.2. In this scenario, the slurry produced from biogas digesters is considered to have no sales value because of several misconceptions and lack of information on it benefits, as discussed in chapter 2. Discount rate of investment is assumed to be 10% as considered by several recent economic studies on energy/ decentralized sector in India (Djanibekov and Gaur 2016, IRENA 2017, Arunachalam et al. 2016). The outcomes for the BAU scenario is presented in figure 4.4 to figure 4.6. Figure 4.4 presents the energy technologies which are selected by the model for cooking, lighting, power and irrigation demand, along with the percentage energy requirements being met by the selected technologies. Figure 4.4 and figure 4.5 presents the shadow price of different energy technologies, along with their levelized cost of energy generation. This will clarify the interdependencies between different energy technologies. Discussions are made after figure 4.6.

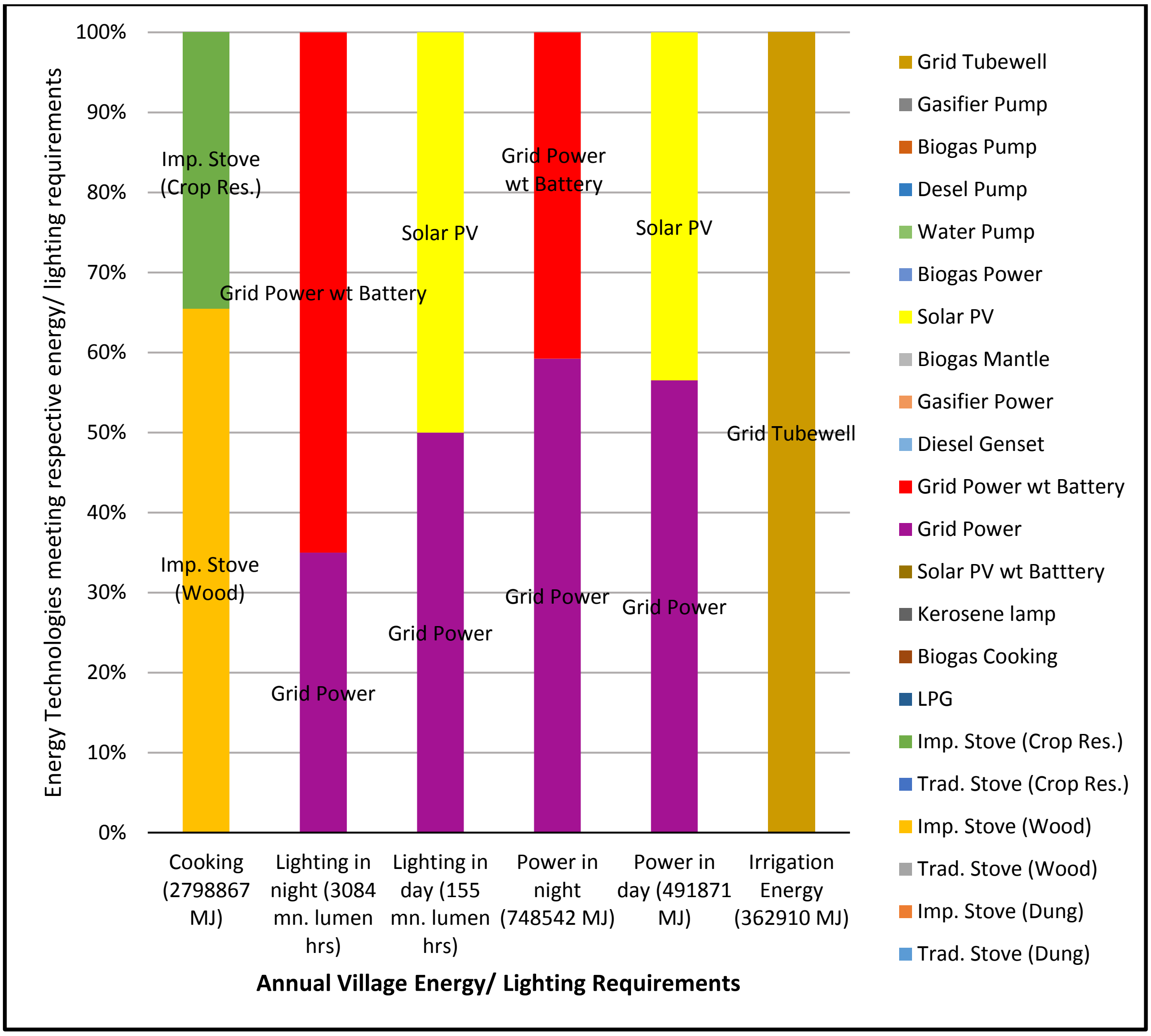

Figure 4.4: Village Energy System (VES) in BAU case: Energy technologies selected by the model and the respective energy requirements met by them

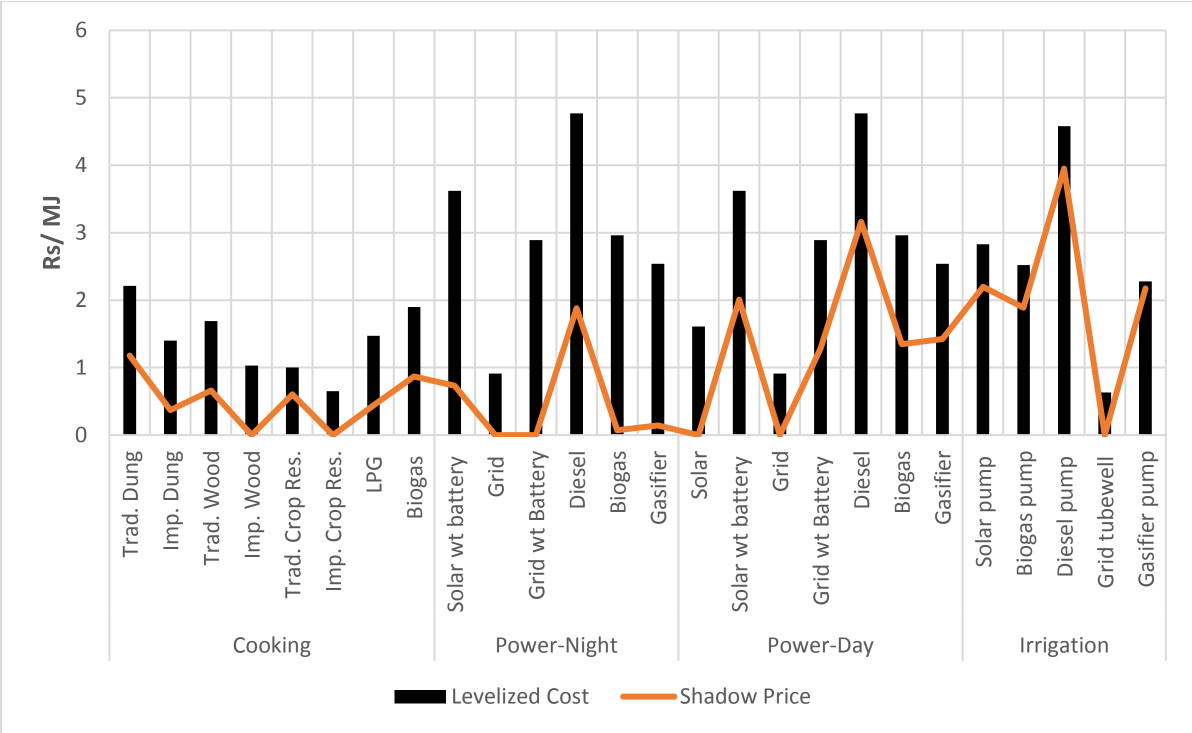

Figure 4.5: VES in BAU case- Levelized costs versus shadow prices of different energy technologies

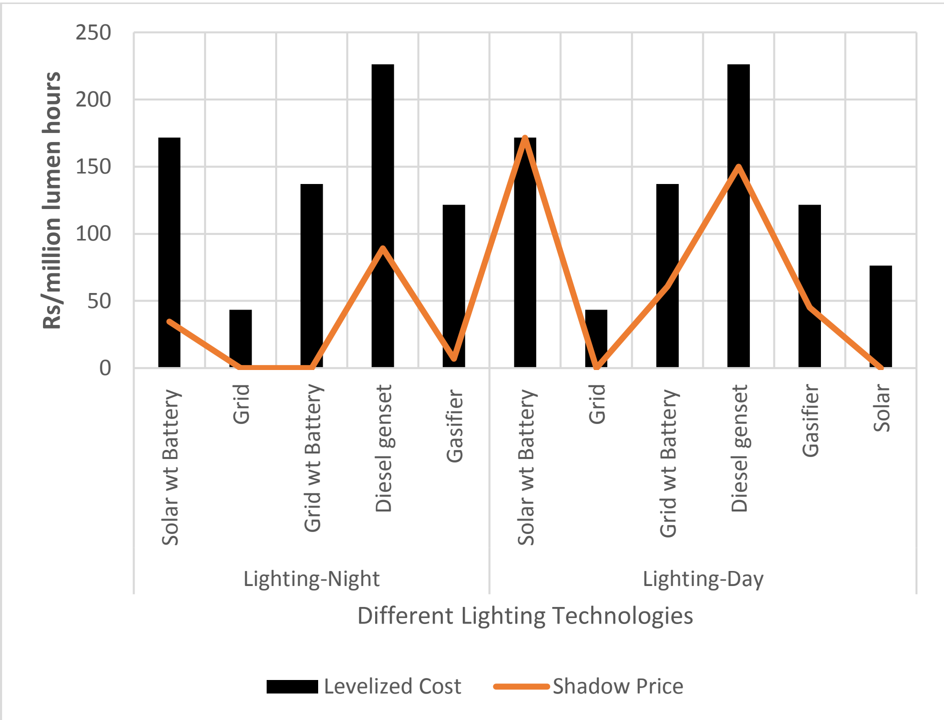

Figure 4.6: VES in BAU case- Levelized costs versus shadow price of lighting technologies

Cooking Energy Demand in BAU case: Referring to leftmost bar in the figure 4.4, model chooses crop residue based improved cook stoves to meet around 35% of village's annual cooking energy demand. After crop residue availability is exhausted, wood residues burnt in improved cook stoves meet village's remaining annual cooking energy demand. In the field research, similar phenomenon was observed where households were observed to be using different bio-energy sources in different seasons depending on their availability, but with traditional cook stoves. In the model output, improved cook stove technology employing local bioenergy resources has come out to be the most preferred option, because with a minimal cost investment, it can give greater thermal efficiency improvements for cooking applications. For instance, Chulika cook stove (improved bio-energy cook stove) available in the market has thermal energy conversion efficiency of 30% with wood viz-a-viz 18% of traditional cook stove. All this comes with the investment of only Rs 2,000 (USD 30) which has a minimum lifetime of 5 years (Jade Oudejans 2012 and TERRE 2010). This makes the levelized cost of useful energy from improved cook stove cheaper than that of traditional cook stoves. Figure 4.7 presents the model output for the case when bio-energy feedstock prices are zero cost (it only presents the snapshot of the results of the model for the cooking energy demand). The interesting thing is that even if the bio-energy feedstocks are perceived free of cost, then also model is suggesting improved cook-stoves with wood or crop residues. This is because that in case of traditional cook stoves, due to their low thermal efficiency, bioenergy can only suffice for limited proportion of cooking energy demand and since bioenergy feedstocks are exhausted earlier, then the model must choose costly LPG or biogas for remaining cooking needs. The model highlights the importance of improved bioenergy based cookstove technology, however, while doing the field research, the same technology was observed to be absent. As observed during the FGDs and the household surveys, the communities were unaware of this technology. It is therefore expected that given good information on the benefits of bio-energy based improved cook-stove and its good distribution network in rural areas, the communities will find it useful to shift to this technology. Further, provided better livelihood opportunities leading to higher opportunity cost of household's time, the opportunity cost of bio-energy collection may increase, and this may make bio-energy usage unviable even with improved cookstoves. This can be easy to infer from the field research in village "OK" where cattle dung cake price in local markets was significantly higher compared to other villages as this village was close to city and the wage rates were higher (Section 2.2.2 and table 3.6) and therefore more number of households had abandoned bioenergy based cookstoves and had shifted to LPG based systems (Appendix table A2.1).

Figure 4.5 presents the shadow prices of different energy technologies from the model, along with their levelized costs of energy generation. Imp. Stove (Crop residues & Wood residues) are chosen by the model for meeting village cooking energy demand. The shadow prices of other cooking energy technologies represent the per unit value by which these variables must be decreased to be accepted by the model. For example, it shows that if levelized cost of LPG is reduced by INR 0.44/ MJ than the model will accept LPG as one of the cooking energy technologies for meeting village's cooking energy demand. In other words, if model has to choose LPG for meeting cooking energy need of the village, then each one MJ of LPG based cooking will increase the objective value i.e the VES cost by INR 0.44. Secondly, shadow price is also useful in assessing the interdependencies between different energy technologies. In figure 4.5, it can be observed that unlike other cooking energy technologies whose respective shadow prices are less than 50% of their respective levelized costs of energy generation, the same is higher than 50% for the crop residue based traditional cook stove, which means that the traditional crop residue-based cooking becomes more expensive in the model compared to other technologies. The reason is as follows. Currently crop residue based improved cook stoves fulfils 35% of cooking energy needs because of its limited stock. Now, if the model instead diverts some crop residues to traditional cook stoves (instead of supplying it to improved cook stoves), then because of low efficiencies of traditional cook stoves and limited availabilities of crop residues, crop residues will not be able to fulfil 35% of cooking energy needs and the model has to now employ some other expensive cooking energy technology.

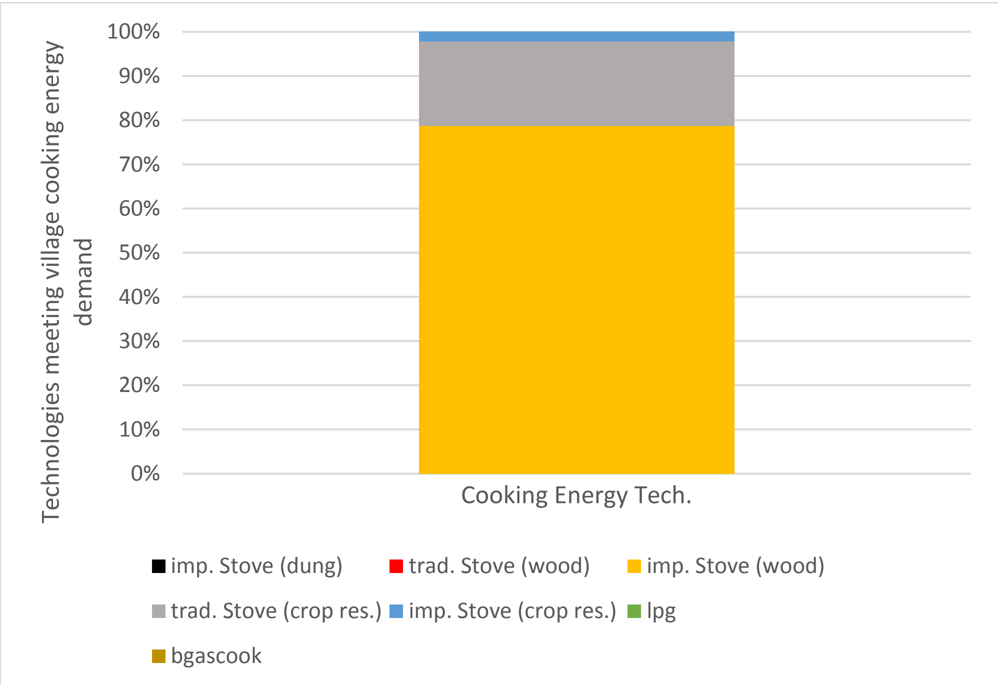

Figure 4.7: VES in BAU case- Cooking energy system with zero bio-energy feedstock prices for cook-stoves

Lighting and power demand in BAU case: In the BAU case, model first chooses state grid electricity for powering electrical equipments and LED lights as the same is highly subsidized. However, as discussed in Chapter 2, there exists constraints with state grid electricity supply and it does not suffice for entire power and lighting requirements of the households/ village. In the day time when grid power is unavailable, model chooses solar PV (without battery) for meeting lighting and power requirements. With the declining solar PV prices in the Indian market, more and more number of households are using solar PV in the villages. During the field research, few surveyed villages already had around 7-10% of its surveyed households using solar systems for lighting and other power applications (as discussed in chapter 2). Please note that solar PV system (without battery) can feed lighting and power equipments directly, however in practical scenario, it may need a small battery bank to compensate for solar radiation fluctuations in day time. Moreover, in the cost calculations of Solar PV power (without battery) in Appendix 1, more than 50% of the system cost has been allocated for the balance of PV system (such as intelligent charge controllers etc) which manage such fluctuations. For meeting lighting and power requirements in night time when grid electricity is absent, model chooses battery banks to fulfil remaining power and lighting demand. These are charged when grid electricity supply is available and thereafter stored power is consumed when grid electricity is absent. During the field research, few surveyed villages even had 30% to 75% of its surveyed households using battery banks for their lighting and power requirements in night time (as discussed in chapter 2).

While discussing lighting in night time, it is important to note that the levelized cost of gasifier-based lighting is cheaper compared to battery-based lighting, however, the latter is chosen by the model because former's shadow price is perceived higher by the model. This is because if model will choose gasifier-based lighting in night time, then the model must now choose some other cooking energy technology (due to limited supply of crop residues) and this will make the cost of cooking energy system and hence village energy system costlier. Similar observation is made for biomass gasifier-based power system viz-a-viz battery-based power system. Another important thing to note is that although biogas power has higher levelized cost of electricity generation compared to gasifier-based power generation, however the shadow price of former is lower than the latter. The reason is same as discussed before where the utilization of crop residues in power sector will make a costly replacement of crop residue-based cooking whereas there is plenty of dung available which can be used for power generation or for cooking needs. These findings indicate that there exist interdependencies between different energy system and with the food energy nexus. However, it is important to note that biomass gasifier could be a very important technology for the rural electrification. Literature shows that biomass gasifier based mini grids are gaining lot of momentum in Bihar and Uttar Pradesh province of India (Palit et al. 2013, Palit and Sarangi 2014). For instance, Husk Power Systems is an Indian company which has installed 84 rice crop residue based biomass gasifier based mini-grids in Bihar province of India serving 200,000 people, within 4 years of its operations (PWC 2016). This is therefore a promising technology for Uttar Pradesh where 2/3rd of the population is dependent on agriculture. The other thing to note is that the shadow price of all lighting and power technologies are higher in day time compared to night time because in the day time because the average lighting price in day time is substantially cheaper in day time due to combination of grid lighting and solar lighting (without battery) whereas in night time the battery increases the average cost of lighting in night time. This makes replacement of solar based lighting costlier in day time.

Irrigation energy demand in the BAU case: Model suggests that state grid electricity based tubewells meet village's 100% irrigation needs as the same is heavily subsidized by the government. During the field research, it was observed that farmers who owned tube wells were fully utilizing the tubewells no matter what time electricity comes, as there are no marginal costs in pumping water. Even, selling water during the night time was very common. Therefore, in the BAU case, no constraints were put in the availability of state grid electricity-based tube-well irrigation. Although, state electricity grid-based tube-well comes out to be winner in the model, during the field research diesel engines were also observed to be very popular amongst farmers. The major reasons for the popularity of diesel engines despite of its financial unviability in comparison to tubewell are: 1) difficulty in getting a tube well connection as it involves lot of red-tape and bribery in the power department, 2) ordinary households perceive high discount rates in making capital investments and getting a tube-well connections involves lot of initial capital (lot of bribe, setting up of local distribution line, electricity poles etc.), 3) households use cheap & subsidized kerosene oil in running diesel engine being unaware of the associated possible damage to diesel engines. Concerning the shadow prices of different irrigation technologies, although the shadow prices of biogas pump, solar pump or diesel pump are around 0.63 Rs/MJ cheaper compared to their respective levelized cost of energy generation, the shadow price of gasifier-based irrigation did not reduce by same figure and is higher. This is again because of the limited crop residue stock (potential gasifier feedstock) that is diverted to cooking sector and any usage of gasifier pump will mean expensive replacement of crop residue based improved cook stove by some expensive cooking energy technology.

Energy System characteristics in BAU case: Table 4.5 below presents the economic as well as external costs stemming from the above modeled village energy system. It shows that annual costs per household (net present value) for this village energy system comes out to be around INR 12,706. On top of that, there will be administrative costs and additional profits that VES entrepreneur will charge for serving the village community (expected to add 30%-40% to the costs). On the other hand, it shows that village communities can receive approximately INR 6,425 per household per year by contributing bio-energy to the VES. An important result of the model is that the average price of lighting and power in day time is significantly cheaper than that of night time. This is because of 2 reasons. Firstly, during night time, village energy system makes use of battery banks which is a costly technology compared to solar (without batteries) which is used in day time. Secondly, the load requirement is high in night time whereas the grid electricity supply is less in night time compared to that of day time, which means battery adds significant costs to night time lighting and power. All this means that it is cheaper to use lighting or power in day time for the village communities. This comparatively low electricity pricing in day time could encourage local cottage industries or other productive activities in the village in day time. This phenomenon can motivate communities to shift some night time power and lighting load to day time.

Table 4.5: Village Energy System (VES) characteristics in BAU scenario

VES Characteristics	Value
Average cooking energy costs (Rs/MJ)	0.899
Average lighting costs in day time (Rs/ million lumen hours)	59.83
Average lighting costs in night time (Rs/ million lumen hours)	104.25
Average power costs in day time (Rs/ MJ)	1.214
Average power costs in night time (Rs/ MJ)	1.717
Average irrigation energy costs (Rs/ MJ)	0.63
Annual Energy System costs per HH (NPV in INR) w/o operator profits	12,706.05
Annual revenue per HH per year (from bioenergy sale in INR)	6,425.52
Total CO2 emissions per HH per year (Kgs/ year)	3.67
Total Health Costs per HH per year (Rs/ year)	2,002.34

4.4.3 Impact of different external drivers on the Village Energy System (different scenarios)

In the previous section, discussions were made on the model results for the village energy system in business-as-usual scenario (Scenario 1). This section will study the impacts of various external factors on the village energy system, and accordingly, different scenarios have been considered. Section 4.4.3.a first explain the assumptions for various scenarios and thereafter in section 4.4.3.b, the model outputs for each scenario will be compared.

a. Different scenarios considered

As discussed in the conceptual framework, there could be different external factors that can influence the energy usage by the communities and its linkages with WEF Nexus. These could be economic, technical, environmental, institutional and behavioral factors. Each scenario, as discussed below, will cater to these external factors.

Scenario 1 (BAU as discussed in 4.4.2): This considered the impact of technical factors on the VES where it included different energy technologies that can make influence energy usage of the communities.

Scenario-2: Scenario with consideration of health costs (Scenario 1 + Health costs): This scenario extends the assumptions of Scenario 1 (BAU) to include environmental and health considerations in the energy planning. This scenario considers the health damage costs due to CO (Carbon Monoxide) and TSP (Total Suspended particles) emissions by energy technologies. CO and TSP were selected because Indian Ministry of New and renewable Energy India (MNRE) consider these gases associated with indoor pollution and has even introduced their emission standards with cookstoves (TERRE 2013). The objective of this scenario is to understand the outcomes of village energy system when the local communities realize the health impacts from different energy technologies and want to minimize the health costs stemming from the system while also minimizing the total economic costs of the energy system.

Scenario 3: Scenario with sale of biogas slurry (Scenario 1 + sale of biogas slurry): This scenario aims to analyze the impact of behavioral changes amongst rural communities. In the BAU scenario, biogas slurry was assumed to be having no sales value due to several local misconceptions and lack of information on its benefits, as discussed in Chapter 2. However, this slurry has a significant fertilizer value (SNV 2011 and IEA undated). In this scenario, it is assumed that the biogas slurry has a sale value in the village market. The price of slurry in local market is assumed to be INR 0.5 per kg because of the following reason. SNV 2011 and IEA undated, mentions that the nutrient content of slurry (digester output) and manure (digester input) are similar, however due to the breakdown of organic matter, the nutrients in slurry are mineralized into a form which is directly and more easily absorbed by the plants and therefore slurry is even a better fertilizer for the crops. So, this means that price of manure and slurry could be same. So, this scenario is an extension of Scenario 1 with the sale value of biogas slurry in local market, but no health and environmental impacts of energy technologies are considered in this scenario.

Scenario 4: Scenario with withdrawal of state subsidies on grid electricity (Scenario 3 + unsubsidized grid electricity): This scenario analyzes the impact of policy change on the energy usage pattern of rural communities. Grid Electricity in Uttar Pradesh is highly subsidized by the government, as discussed in Chapter 2 (table A1.1). Planning Commission 2014 presents the true cost of power in India and other states of India. Ibid presents the true cost of power in Uttar Pradesh in year 2011 to be INR 3.7/kWH. Ibid also presents this cost for India for year 2013-2014, however not for Uttar Pradesh. Using the trend of growth of true cost of power in India between year 2011 and year 2013-2014, this year 2011 data for Uttar Pradesh was adjusted for year 2013-2014 as INR 4.32/ kWH. In this scenario, it is assumed that state electricity board provides electricity to households without any state subsidies. Please note that state electricity board will also have some operational costs and profit margins which is not included here. However, the average spot power market price in Indian Energy Exchange has gone down significantly in last 2 years and is averaged at INR 2.49/ kWh in July 2017 (Indian Energy Exchange website). This means that that considering unsubsidized grid power @ INR 4.32/ kWh is well justified for this scenario. It is to be noted that this scenario also considers the sales value of biogas slurry & is an extension of Scenario 3.

Scenario 5: Scenario with state subsidies on renewable power technologies (Scenario 4 + renewable subsidies): High initial capital costs for decentralized energy systems such as Solar PV, biomass gasifier etc, is generally considered to be a bottle neck for the widespread of these technologies. To improve viability of decentralized renewable energy technologies, state as well as national energy departments (such as MNRE) have introduced several subsidy programs in rural areas. UPSERC 2014 mentions that MNRE provides capital subsidy to renewable energy based decentralized energy mini grids at the rate of around 30% of its benchmark costs. Solar Water Pumps have gained significant attention in the recent years and are receiving state subsidies up to 70% to 90% of its benchmark costs (Intersolar website). In this scenario, the impact of such subsidy programs will be analyzed in the energy usage pattern of the communities. It is to be noted that this scenario also considers the sale price biogas slurry.

Scenario 6: Scenario with high discount rates (Scenario 5 + high discount rates): Nelson et al. 2012 and FICCI 2013 identifies the financial barriers in the success of renewable power in India, and highlights that the rate of debt for renewable power projects in India is very high (13-14%) compared to other developed countries and this make the cost of RE power projects very expensive in India. In addition, ibid highlights that unlike other power technologies, renewable energy technologies are perceived as risky investments by Banks. This problem further aggravates when renewable power projects are small and are remotely located, also resulting in higher transactions costs for Banks. All this makes the investment in decentralized renewable energy a costly investment. Therefore, to understand such problems, high discount rate of 14% is considered in this scenario, compared to 10% discount rates considered in previous scenarios. It is to be noted that this scenario also considers the sale price of biogas slurry.

b. Results of different scenarios

This section applies the above discussed external factors on the VES model as a separate scenario. It then compares every VES component (energy subsystem such as cooking, lighting etc. separately) in these 6 scenarios, one by one.

<u>Cooking Energy in different VES scenarios</u>

Figure 4.8 below presents the energy technologies chosen by model for fulfilling the cooking energy requirements of the community in different VES scenario, whereas figure 4.9 below presents the shadow price of different cooking energy technologies in different VES scenarios. These are followed by the discussions on the same.

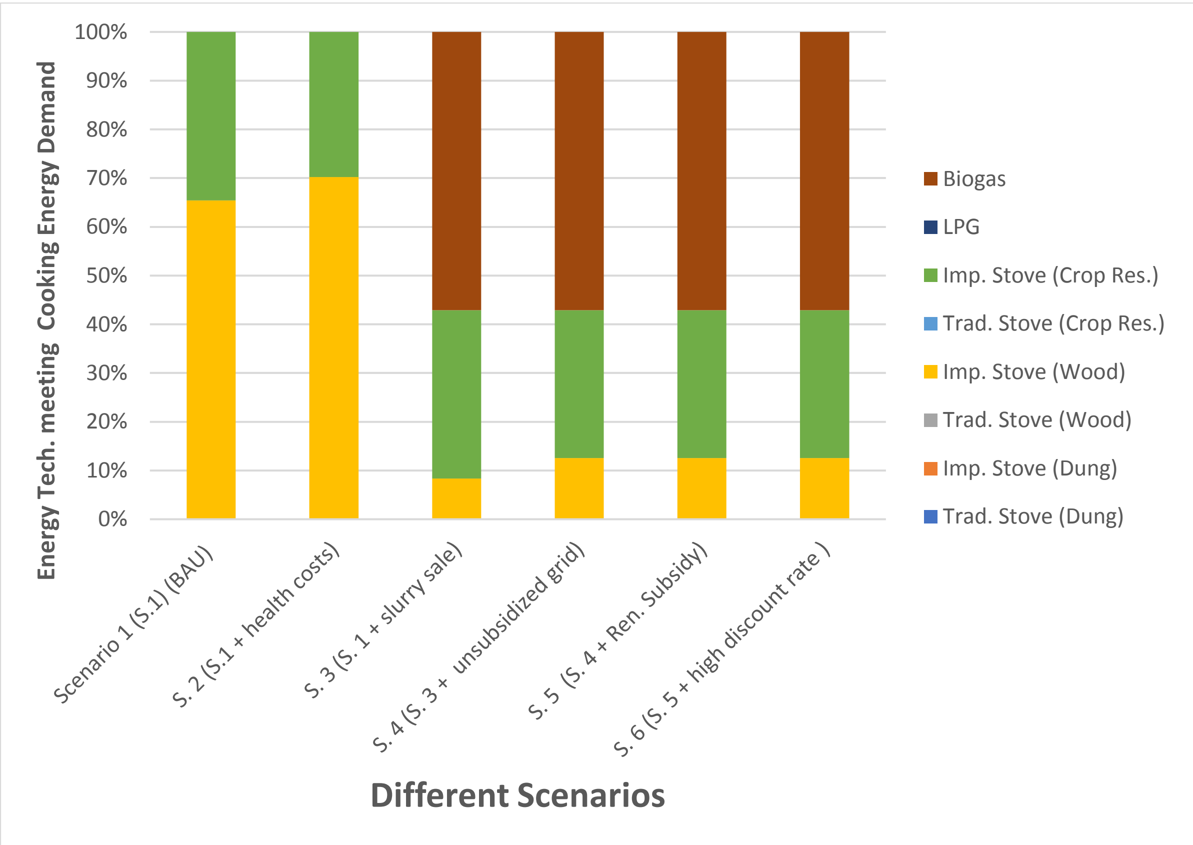

Figure 4.8: VES- Village cooking energy system in different scenarios

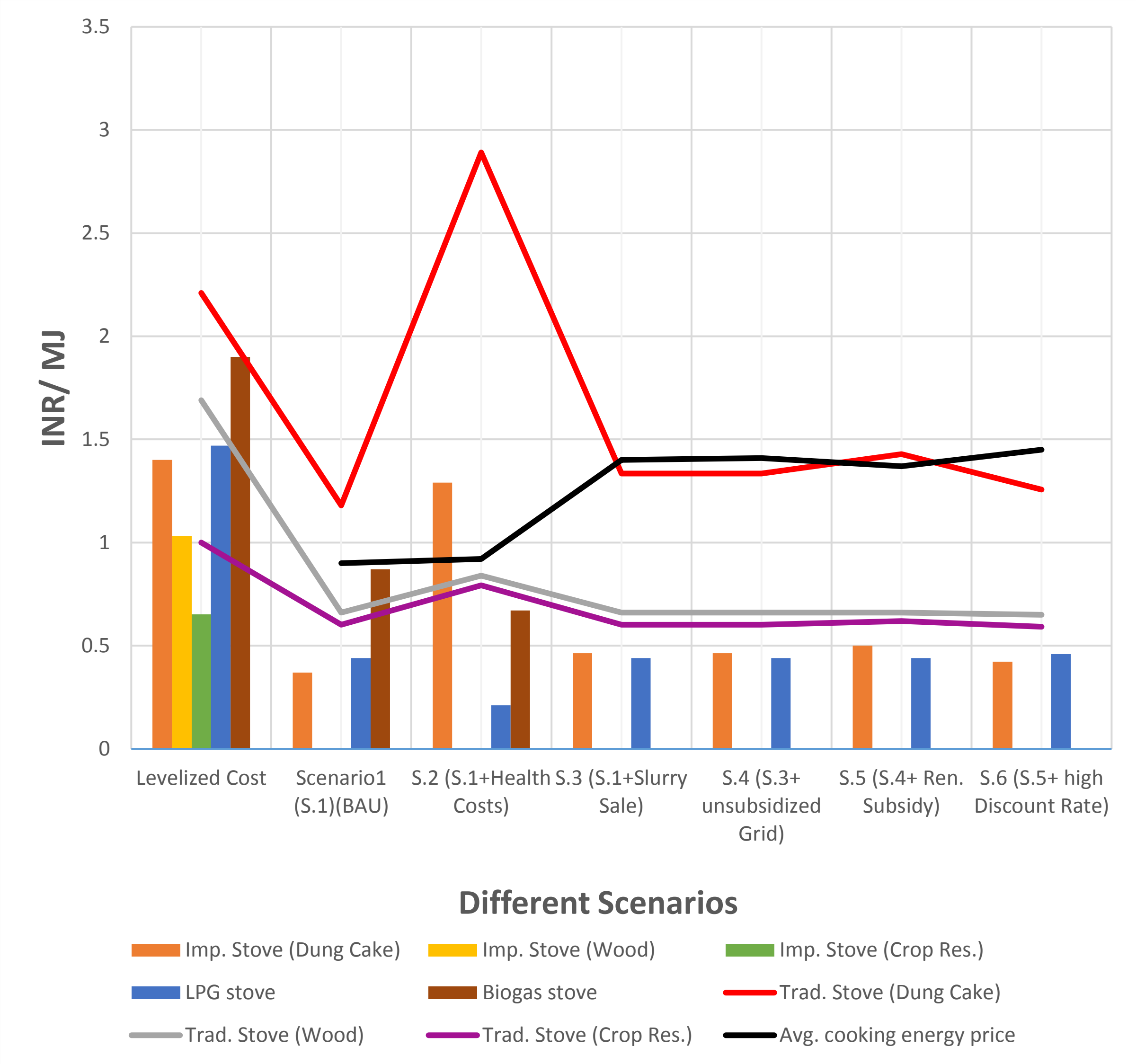

Figure 4.9: Levelized cost v/s shadow price of different cooking energy technologies, and average cooking energy price in different scenarios

The discussions on Scenario 1 results were already made in section 4.4.2, however the same is again summarized here. In scenario 1, model first chooses available crop residues stock with improved cook stove as the major cooking energy system for the village, and once the crop residue stock expires, model chooses available wood with improved cook stove.

Scenario 2 considers the health costs. Comparing scenario 2 with scenario 1, following are the major changes. Firstly, model now chooses improved cook stove with wood as the first choice of cooking energy system, as its health damage costs per MJ of useful energy is almost half compared to that of crop residue based improved cook stove. Once the stock of wood finishes, it uses improved cook stove with crop residues. Compared to Scenario 1, crop resides based cooking decreases by 13% in scenario 2 because of health cost considerations. Secondly figure 4.9 shows that due to associated health damage costs, the shadow price of all traditional cook stove-based energy system and even dung cake based improved cook stove increases as compared to scenario 1, whereas shadow price of LPG and biogas decreases significantly. This means that if there is scarcity of wood and crop residues in village, then the opportunities of LPG and biogas technology will increase.

In Scenario 3, unlike previous scenarios, model considers the opportunity to biogas slurry in local markets. In this scenario, biogas becomes a prominent cooking energy technology. Since biogas also competes for lighting and power system, its meets around 55% of village's cooking energy needs after meeting village's night power requirement (as shown in figure 4.13). For the remaining amount of cooking energy, model first utilizes available crop residues stock with improved cook stove. After crop residue stock finishes, remaining small amount of cooking energy demand is met by wood based improve cook stove. Further in this scenario, average cooking price increases because biogas is a costly technology however net cost of energy system decreases because of the sale of biogas slurry. Another interesting aspect of the scenario is that shadow price of dung cake based traditional and improved cookstove increases compared to scenario 1, because using dung for dung cake will not yield slurry as in the case of biogas and slurry has a price attached to it in this scenario. So, in this scenario, opportunities with dung cake-based cook stoves further decreases. This scenario shows that biogas-based cooking could be a very viable cooking energy technology provided biogas slurry is perceived as a valuable fertilizer by local communities and the misconceptions on this technology are eradicated.

Scenario 4 considers the withdrawal of government subsidies on grid electricity, but still considers sales value of biogas slurry. The impact to cooking energy system in this scenario comes through village's lighting system where gasifier replaces the grid powered battery-based lighting in night time. These crop residues for gasiifier comes by diverting some crop residues from cooking energy system. This leads to around 12% reduction in the final cooking energy demand being met by crop residues, compared to Scenario 3.

Scenario 5 is an extension of Scenario 4, where model assumes around 30% capital subsidy on renewable power technologies including improved cook stoves as well as biogas technology. Although the cooking energy pattern in the scenario does not changes as compared to Scenario 4, however the shadow price of traditional cook stove-based technologies increases by up to 7% making usage of traditional cook stove-based technologies even costlier in this scenario. Secondly, in this scenario, the average cooking energy price decreases by around 3% due to the subsidies given to new and improved technologies.

Scenario 6 is an extension of Scenario 5, which considers high discount rates in energy investments. Discount rate basically signifies that the cost of making investment. This scenario does not change the cooking energy pattern, however the shadow price of traditional cook stove-based bioenergy decrease between 2%to 12% as compared to scenario 5, whereas the shadow price of LPG cook stove increase by around 5% as its requires an initial investment in the connection fees. This means that if the cost of investment is high, then the opportunities with traditional cook stove will increase, whereas opportunities with improved and modern technologies will decrease.

Lighting usage in different scenarios

Figure 4.10 below presents the lighting energy technologies chosen by model for fulfilling the lighting requirements of the community in different scenario. Figure 4.11 and 4.12 below presents the shadow price of different lighting energy technologies in different scenarios. It is to be noted that shadow price of kerosene, LPG and biogas mantle-based lighting has been shown separately in figure 4.12 because their levelized and shadow prices are almost 1000 times more than other technologies and both are difficult to be shown on the same graph.

Scenario 1 is the BAU scenario which was already discussed in section 4.4.2, but the same is again briefly reproduced here. In scenario 1, model chooses grid electricity-based lighting in day as well as night time. When grid is unavailable, it chooses solar lighting in day time and battery-based light in night time. Here, battery is charged by grid electricity whenever it is available. In scenario 2 which considers health costs of energy technologies, model still chooses similar lighting system as in Scenario 1. However, the analysis of shadow prices indicates that the shadow price of gasifier lighting in night time almost becomes zero because of the following reason. The health impacts associated with crop residue-based cooking reduces its consumption in cooking energy sector, and the model suggests the surplus crop residues to be used for gasifier-based power production in night. In this scenario, a possible per unit consumption of gasifier lighting in night will replace some part of gasifier-based power in night which is cheaper to replace compared to some part of crop residue-based cooking energy consumption as was the case in scenario 1 and this makes the shadow price of gasifier-based lighting low in night time in this scenario. On the other hand, as shown in figure 4.9, because of comparatively high health damage costs, shadow prices of diesel genset based and kerosene-based lighting in day and night have increased in this scenario compared to scenario 1.

Scenario 3 considers the opportunity of sale of biogas slurry. In this scenario, model still chooses the same lighting technologies in day and night, however the shadow price of biogas-based lighting almost reduces by 50% compared to Scenario 1, which is because of the selling opportunity of biogas slurry. However, Biogas based mantle remains a costly lighting technology and is not selected by the model. In scenario 4 which considers removal of grid subsidies, grid electricity-based lighting still wins over the other lighting technologies in both day and night time. When grid is unavailable in the day time, model chooses solar lighting in day time. However, in the night time, when grid is unavailable, grid powered battery-based lighting loose the competition to the gasifier-based lighting. This is because biogas becomes the most cost-effective cooking option in this scenario and this creates an opportunity to use crop residues in other energy systems and this makes the shadow price of gasifier-based lighting in this scenario low and it is eventually selected by the model. On the other hand, the shadow price of grid powered battery-based lighting increases in this scenario because of removal of subsidies from grid electricity. Average lighting price in day time increases in this scenario compared to scenario 3 because of increase in grid lighting price, whereas in the night time it decreases because grid powered battery-based light is replaced by gasifier-based lighting.

In scenario 5 which considers capital subsidies on renewable energy technologies, solar light wins over the grid-based lighting in day time and caters to the entire day time lighting demand of village. In night time, grid electricity still provides the cheapest lighting solution and when it is unavailable, it selects gasifier-based lighting as in previous scenario. It is to be noted that capital subsidies favor solar technology more compared to gasifier or other technologies because unlike other technologies the entire cost component of solar is the initial capital investment. In the day time, the shadow price of gasifier-based lighting increases because compared to solar it Is benefitted less from capital subsidies. Another interesting thing to notice is that the government subsidies on other technologies such as gasifier or biogas may not be at all useful as these technologies are highly site specific. It may happen that entrepreneurs avail capital subsidies for such technologies, but these projects ultimately fail as the technologies also compete for feedstocks with other energy systems. Overall the average lighting price in both day and night time decreases in this scenario compared to scenario 4 because of the renewable power subsidies.

Scenario 6 considers high cost of investment and this scenario simply negates the impact of capital subsidies on renewable. Solar PV now loses to grid electricity-based lighting and when grid electricity is absent then solar lightings are used. There is no impact on lighting usage in night time as was the case in scenario 5. Compared to Scenario 5, this scenario increases the shadow price of all those lighting technologies that need high initial investment such as battery or solar, whereas technologies which don't need high initial investment experience decrease of shadow prices. Overall the average price of lighting increases in this scenario as any investment becomes expensive in this scenario.

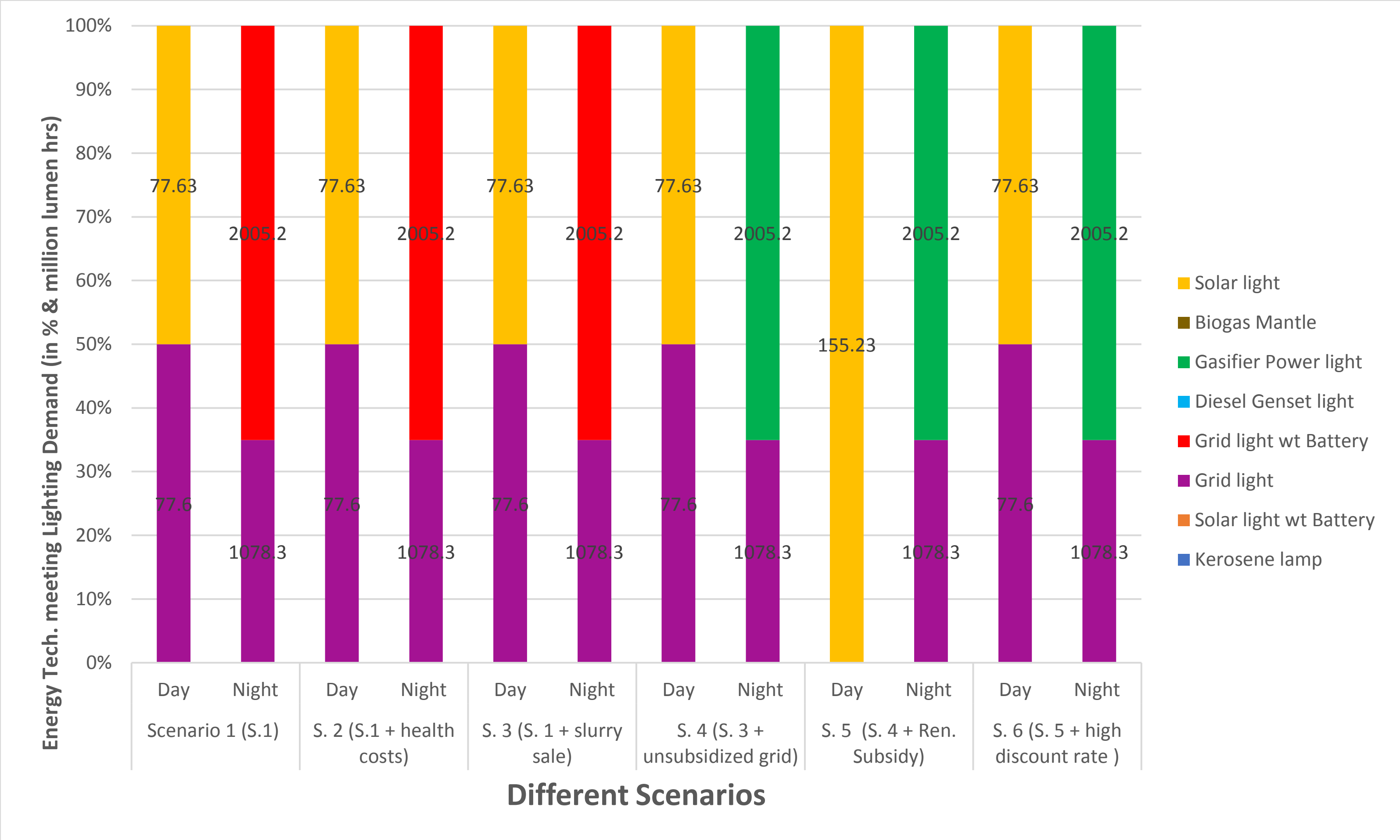

Figure 4.10: VES- Village lighting system in different scenarios

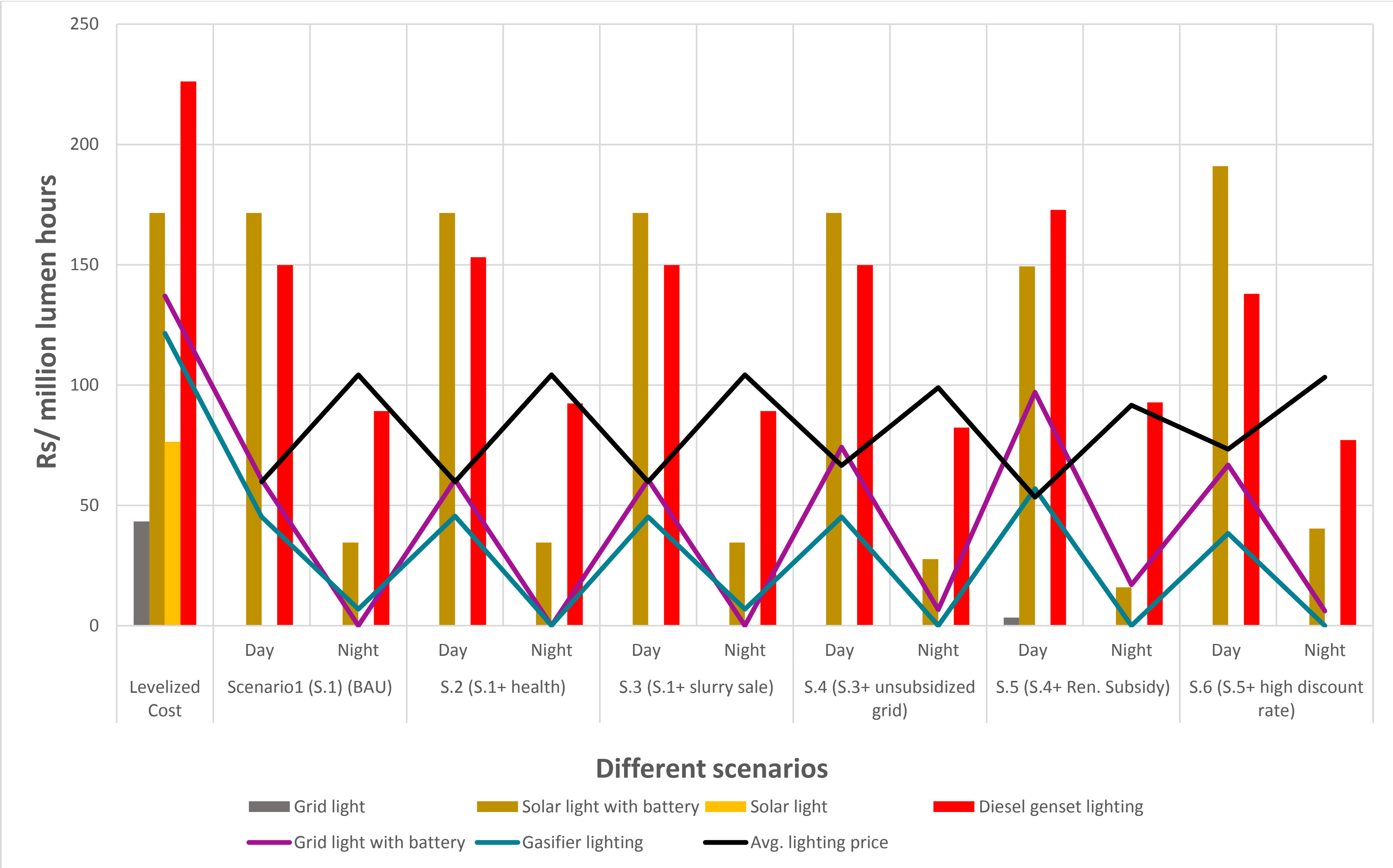

Figure 4.11: Levelized cost v/s shadow prices of different lighting technologies, and average lighting price in different scenarios (except for kerosene, LPG and biogas lighting)

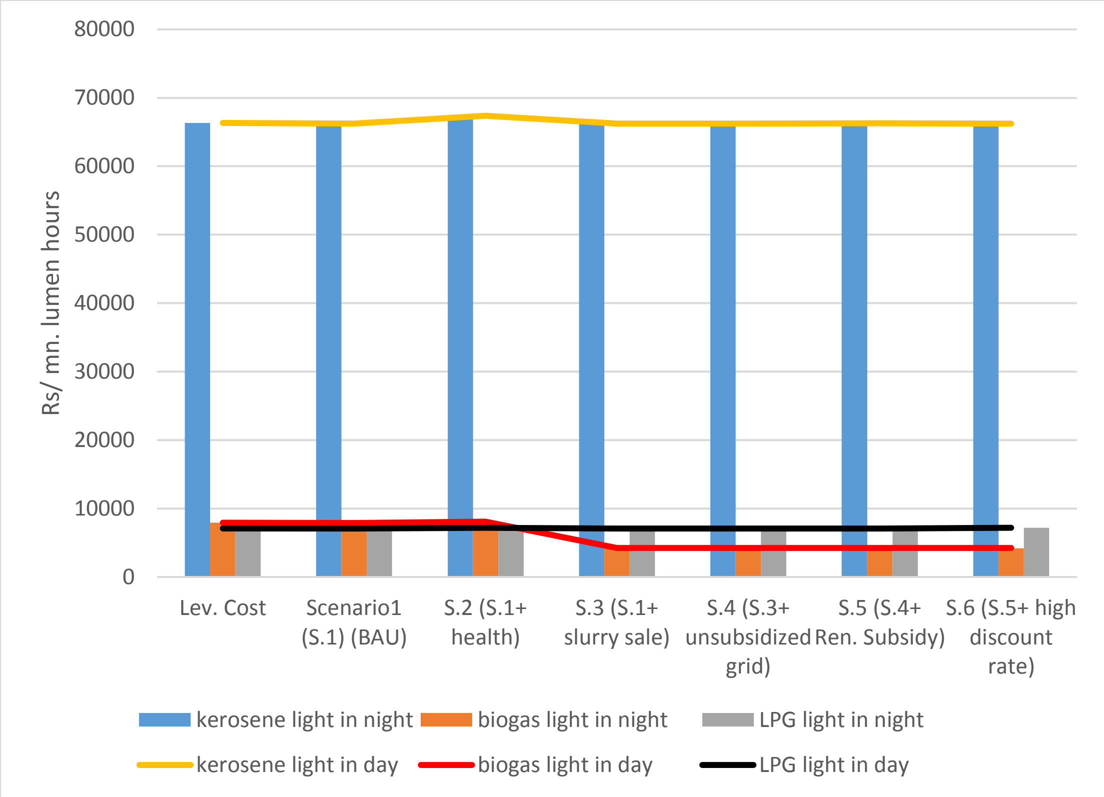

Figure 4.12: Levelized cost v/s shadow prices and average lighting price of kerosene, LPG and biogas lighting in different scenarios

Power usage in different scenarios

Figure 4.13 below presents the power technologies chosen by model in different scenarios. Figure 4.14 below presents the shadow price of different power technologies in different scenarios. Scenario 1 (BAU) was already discussed in previous section. Here, grid electricity is the winner in day time and when it is unavailable, model recommends solar power. In night time, model again selects grid electricity and when it is unavailable, model selects battery (charged by grid electricity).

In Scenario 2, which considers the health costs of the energy technologies, model results for day time are similar as that of scenario 1. In night time, grid power is again selected by the model, however when it is unavailable, biomass gasifier (crop residue based) is used for meeting the power needs of the community, and when the crop residue stock expires, battery power meets the remaining power needs of the community. The reason for this change is as follows. Because of the health costs, model uses less amount of crop residue-based cooking in Scenario 2. The surplus crop residues can now be diverted to other energy sectors and this reduces the shadow prices of crop residue-based technologies in other sectors. Now as shadow price of biomass gasifier technology is higher in lighting and irrigation sectors (where they compete with cheaper technologies), model uses gasifier power for meeting power demand in night time. This reduction of battery (grid charged) based power also result in slight reduction of average power price in night time. For the shadow pricing, as expected, the shadow price of diesel power increases both for day time and night time. Compared to Scenario 1, model shows increased shadow price for biogas power in Scenario 2 because it still has some harmful emissions compared to grid and battery-based power.

In scenario 3, which considers the opportunity of selling biogas slurry in the market, biogas production becomes cost effective and is also used for running generator for power usage in night time when grid power is unavailable. In this scenario, day time power utilization pattern is like that of Scenario 1, although the shadow price of biogas power in day time reduces significantly. Because of the slurry sale and its benefit to biogas, the shadow price of all other power technologies increases significantly compared to Scenario 1. The usage of biogas power slightly increases the average power price in night, however the net present value of the entire power system decreases because of the revenue from the sale of slurry.

In scenario 4, which considers withdrawal of state subsidies from grid power, the power usage pattern remains the same as in scenario 3, as grid is still the most cost-effective option. However as expected the shadow price of battery (charged from grid) based power increases as compared to Scenario 3. As expected, this withdrawal of grid subsidies makes the average power price slightly high compared to Scenario 3.

Scenario 5 considers capital subsidies on renewable energy technologies. Here, with only 30% capital subsidy, solar power wins over the grid power in day time and now fulfil the entire power requirement of the village. However, the pattern of power supply in night time remains same as that in Scenario 4. The important point to note here is that the capital subsidies benefit solar technology more compared to other renewable power technologies as solar investment involves major capital investment and minor operation costs whereas other technologies also require significant operational costs. This gives more benefit to solar technology from capital subsidies. This is the reason that shadow prices of both non-renewable and other renewable power technologies increase in day time in Scenario 5 compared to Scenario 4. Whereas in night time, as the competition is with grid-based power (unsubsidized), therefore shadow price of all renewable based technologies (subsidized in this scenario) decreases as compared to Scenario 4. The subsidies on renewable technologies decreases the average power price for both day and night time.

Scenario 6, which considers high discount rates on energy systems, reverse the capital subsidy benefits to solar technology. This is because solar power requires high initial capital investment and high discount rates makes more harm to technologies needing high initial investment. Shadow price of all other technologies in this scenario decrease as compared to Scenario 5 because compared to solar they need lesser initial capital but higher operational costs. In the night time, there is an increase in the shadow price of biomass gasifier-based power because its competition is with grid-based power and gasifier requires higher initial capital investment compared to grid power supply. The average price of power increases in Scenario 6 because high discount rates makes solar and biogas technologies expensive.

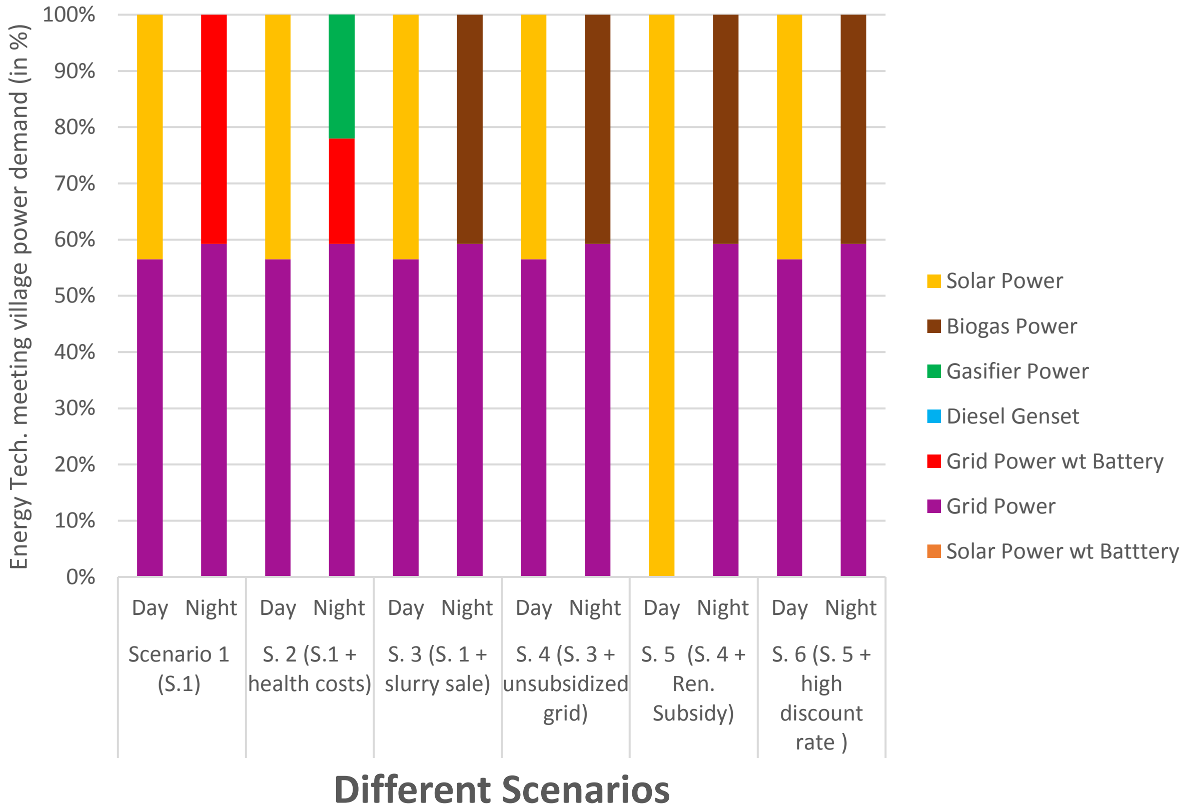

Figure 4.13: VES- Power System in different scenarios

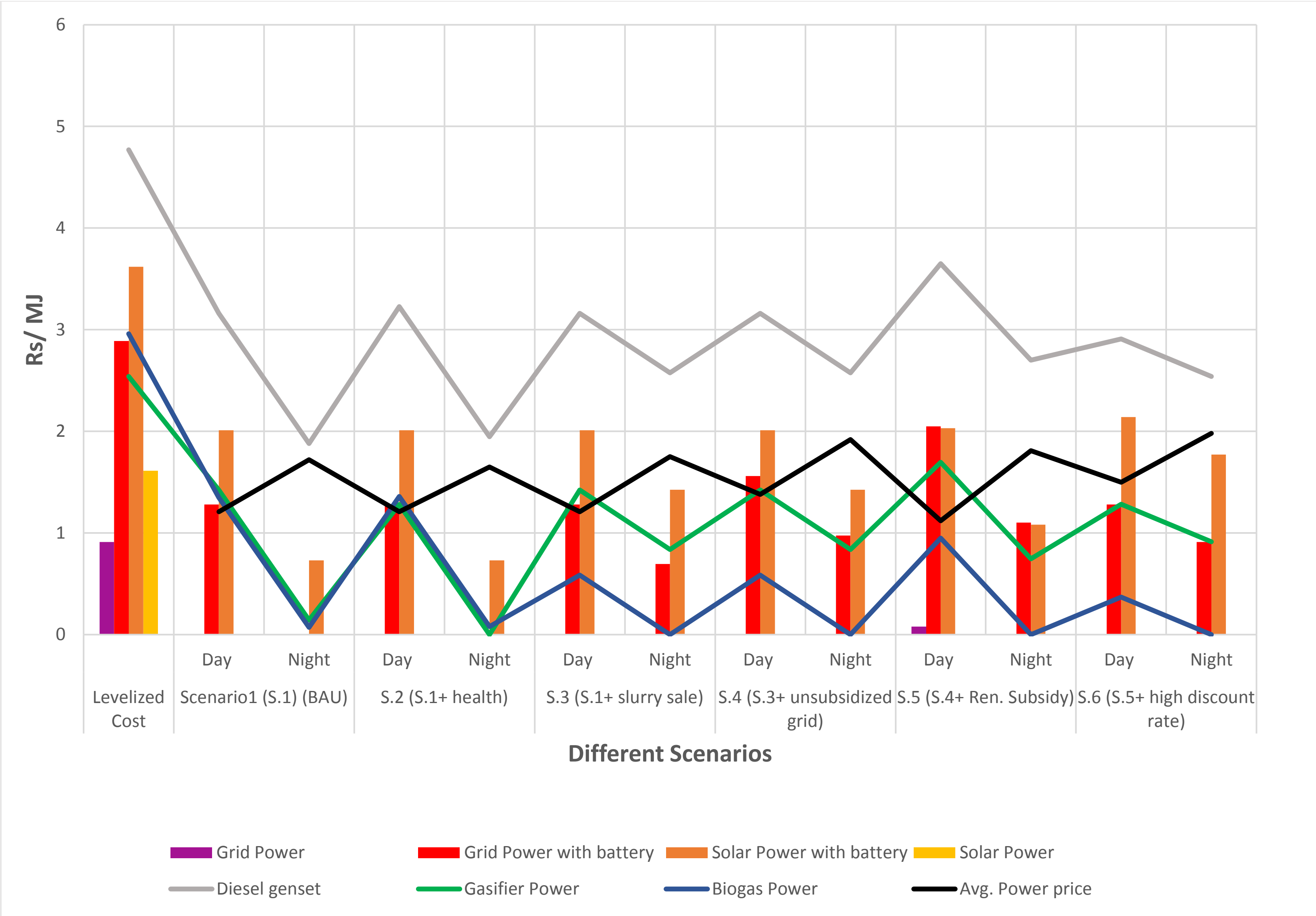

Figure 4.14: Levelized cost v/s shadow Price of different power technologies, and average power price in different scenarios

Irrigation Energy in different scenarios

Figure 4.15 below presents the irrigation technologies chosen by the model in different scenarios, whereas figure 4.15 presents the shadow prices of different irrigation technologies in different scenarios. As discussed in BAU case in section 4.4.2, model selects grid electricity-based irrigation for fulfilling the entire irrigation demand of the village. In scenario 2, which considers the health costs of energy technologies, there is no change in the irrigation energy usage pattern of the communities. The analysis of shadow prices for scenario 2 in comparison to scenario 1 shows an increase for diesel-based irrigation and a decrease for gasifier-based irrigation. The increase for diesel-based irrigation is due to health costs. The decrease for gasifier-based irrigation is due to the surplus crop residues from cooking energy system, which is eventually diverted to power sector, however any potential diversion of crop residue to irrigation in Scenario 1 would have been costlier compared to scenario 2 because then crop residue cooking would have to be replaced by costly wood-based cooking energy.

In Scenario 3, which allows selling of biogas slurry in market, shadow price of biogas-based irrigation decreases, however still it is unable to win over subsidized grid-based irritation. On the other hand, shadow price of gasifier-based irrigation increases in this scenario because crop residues are fully utilized in cooking energy sector and potential diversion of crop residues to other energy usages would mean replacement of crop residue-based cooking with other costly cooking energy technology.

Scenario 4 considers withdrawal of grid subsidies, however still grid based irrigation wins. However, in this scenario shadow price of all other irrigation technologies decreases significantly as cost of grid-based irrigation increases significantly. This improves the potential avenues for other technologies. In this scenario, biogas-based irrigation shows significant low shadow price which means that out of the other irrigation technologies (other than grid), it would be the cheapest irrigation option, however it suffers from supply constraints as model finds it more appropriate to divert dung to cooking energy system.

In Scenario 5 which considers capital subsidies on renewable technologies, solar water pump replaces the unsubsidized grid irrigation. However, it is to be noted that the shadow price of unsubsidized grid irrigation is only INR 0.28/ MJ. This means that if the cost of this option is reduced by INR 0.28/ MJ than the same will be accepted by the model. Comparing unsubsidized grid irrigation (INR 1.2/ MJ) and subsidized grid irrigation (INR 0.63/ MJ), this means that subsidized solar irrigation will only be able to compete with grid-based irrigation when the government withdraws subsidies from the latter. Secondly, in this scenario, shadow prices of other irrigation energy technologies increase as compared to Scenario 4 and this happens because of 2 reasons. Firstly, solar technology involves high upfront capital investment compared to its competing technologies here and therefore capital subsidy makes more prominent impact on solar technologies. Secondly, considering its high upfront costs and potential, state government promote solar water pumps and offer significantly high capital subsidies of around 70% of its benchmark cost, compared to 30% to other renewable based technologies.

Scenario 6 is the extension of Scenario 5 which considers high discount rates. This scenario reverses the impact of capital subsidies and grid irrigation is chosen. This scenario increases the shadow prices of solar and gasifier-based irrigation, but the greatest impact is on the former because of its high initial capital investment requirement. The average irrigation cost in this scenario is like scenario 4 because of unsubsidized grid-based irrigation.

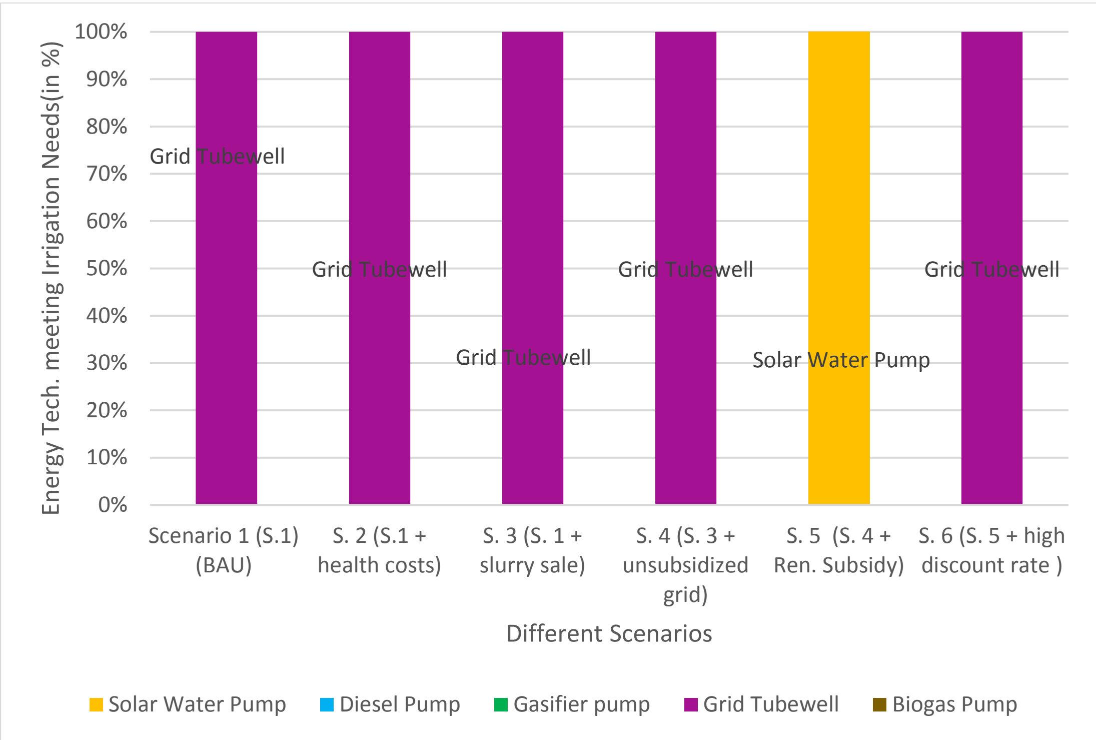

Figure 4.15: VES: Irrigation Energy System in different scenarios

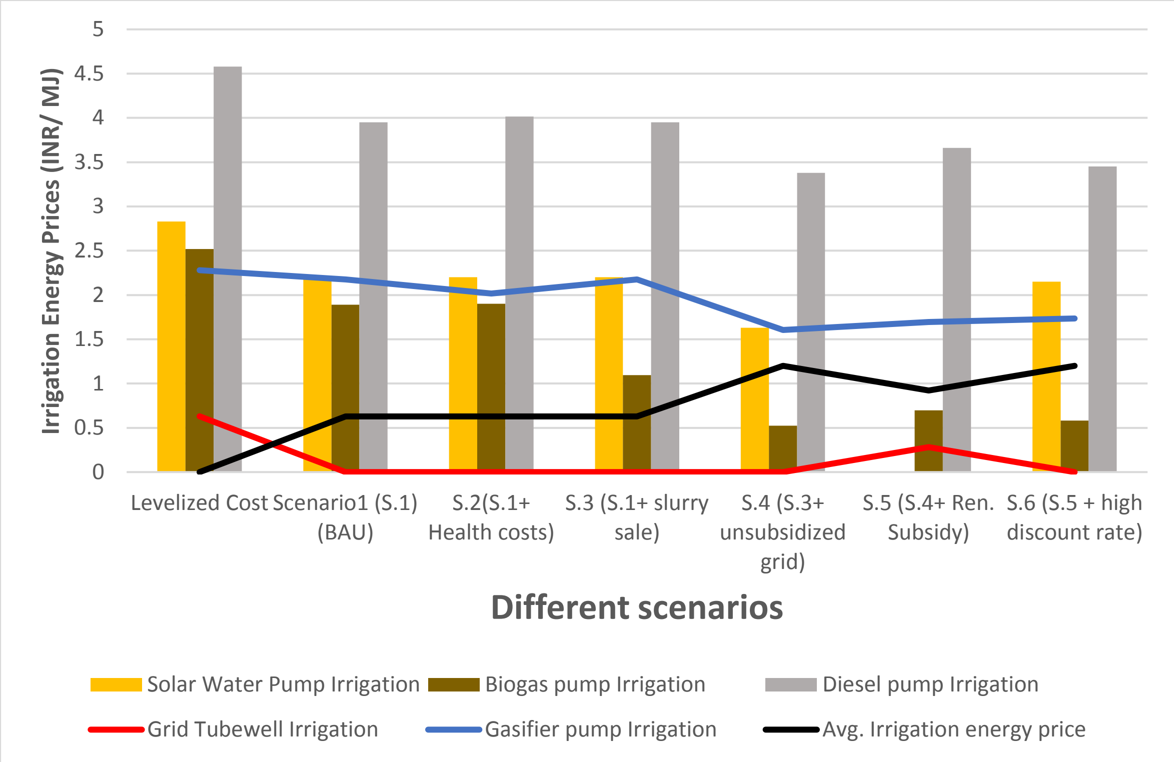

Figure 4.16: Levelized cost v/s shadow price of different irrigation technologies, and average irrigation energy price in different scenarios

<u>Energy System Characteristics</u>

Figure 4.17 presents the energy system characteristics in different scenarios, which is followed by a discussion on the same.

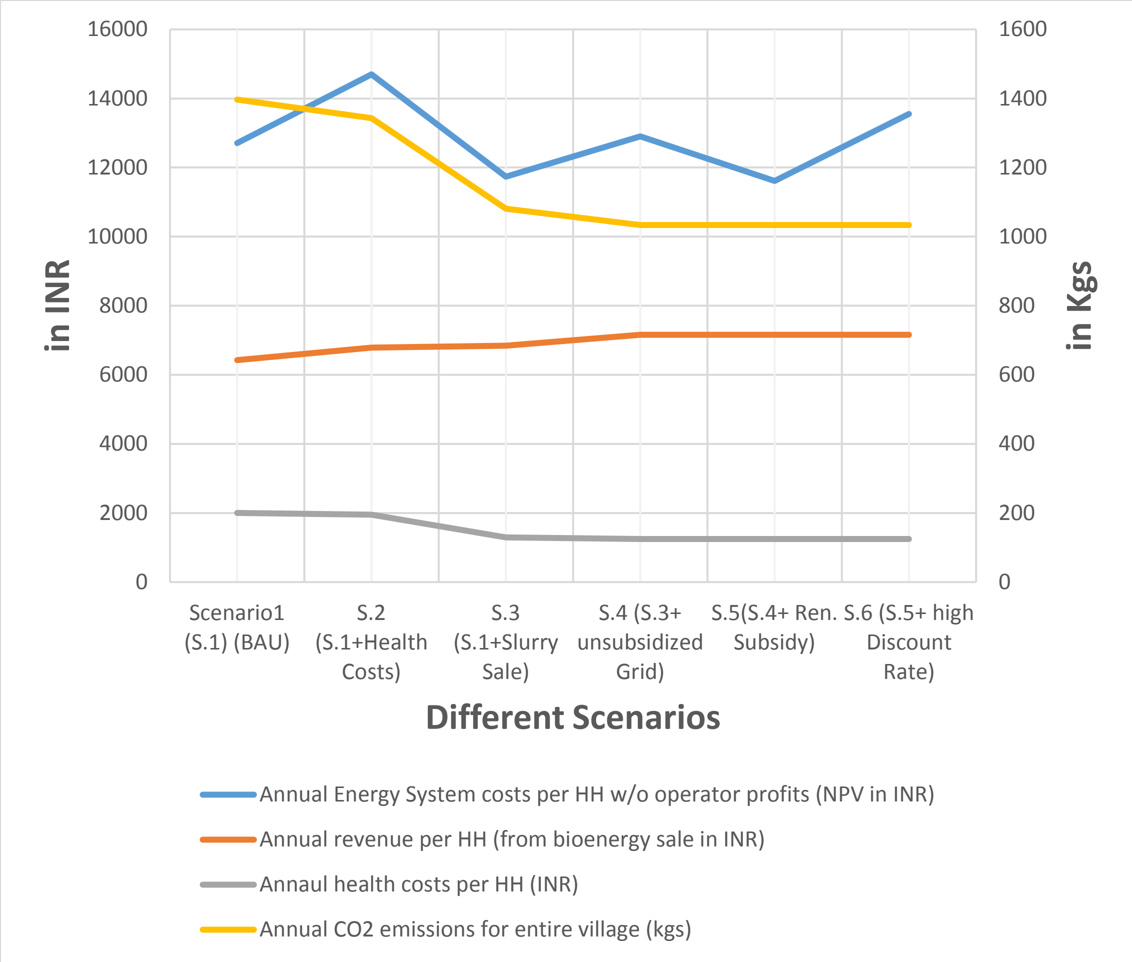

Figure 4.17: VES: Energy System characteristics in different scenarios

Figure 4.17 shows that the annual energy system cost per HH (NPV) rises from Scenario 1 to Scenario 2 because of the added health damage costs associated with energy technologies. This is mainly from the crop residues used in cooking and power sector. Going to scenario 3, this cost decreases to even below Scenario 1 level because scenario 3 utilizes cleaner biogas technology for meeting significant part of its cooking and power needs and the produced biogas slurry is sold back in the local market and this reduces the net system cost. This cost further increases in scenario 4 compared to scenario 3, because it considers removal of subsidies from grid electricity which covers significant lighting, power and irrigation needs of the community and this increases per unit electricity costs to 25% for lighting and power usage and around 50% for irrigation usage. Renewable subsidies in Scenario 5 replaces grid electricity with solar for lighting and power in day time and for all irrigation needs and this leads to overall reduction in net costs of VES. Going to Scenario 6, the costs again increase because high discount rates make existing usage of renewable energy technologies (selected by the model) costlier in this scenario.

Health costs and CO2 emissions decreases from Scenario 3. This is because of the changes in cooking energy system where wood and crop residue-based cook-stove energy is replaced with biogas-based cooking. Annual household revenues per HH increases from Scenario 3 because available bioenergy of households (available for energy usage) is mostly consumed by the VES for biogas and modern bio-energy based cooking technologies.

The above discussions show that comparing annual energy system costs, environmental costs and household revenues, biogas technology (which is used from scenario 3 onwards) can provide the best welfare gains to the village community. Therefore, if misconceptions around biogas technology are eradicated, then this technology has a great potential.

4.5 Conclusions and Recommendations

Decentralized energy systems can play a significant role in strengthening the rural energy supplies. The existing literature on decentralized energy system modelling suffer from several shortcomings, as most of them restrict themselves to few limited energy sources and technologies (energy systems), ignore their interdependencies as well as their linkages with food security, and give little emphasis on demand side energy management (DSM) opportunities with DES. This study tried to bridge the above gaps by developing an optimal village energy model in GAMS. The model identifies an optimal village energy system (VES) for meeting village's cooking, lighting, power and irrigation needs, while minimizing VES's net annual costs (NPV) considering the time horizon of 15 years and discount rate of 10%. Several scenarios were considered to analyze the impacts of external factors on the outputs of VES. The major findings are summarized below.

Energy systems interdependencies and linkages with food security

Results confirmed energy systems interdependencies for the rural communities. For instance, results showed that the levelized cost of electricity generation from biomass gasifier power system is 2.54 INR/ MJ as compared to 2.89 INR/ MJ from grid electricity-battery based power system. However, model selected the latter for fulfilling village's night time power needs while it assigned higher shadow price of 0.143 INR / MJ to the former. This happened due to the limited availability of crop residues in the village, as each unit production of gasifier-based lighting or power would have led to the replacement of some portion of crop residue-based cooking in the village with some another expensive cooking energy technology resulting in overall increased VES costs. This means that if village lighting or power system would have been modelled in isolation to cooking energy system, then crop residue-based gasifier technology would have won over battery based lighting or other power systems. However, if the energy systems interdependencies are considered, then the results are opposite and gasifier technology loses. Another similar result was the comparison of shadow prices of biogas power and gasifier-based power in the BAU scenario results. The above discussion shows that while modelling decentralized energy systems (utilizing local bioenergy resources), the interdependencies between cooking, lighting, power and irrigation systems should not be ignored. This has practical relevance. In the past, government supported gasifiers-based power projects in different parts of the country, however several of them failed (Palit & Sarangi 2014, Palit et al. 2013). Overlooking the energy systems interdependencies and their linkages with food security could be a reason for the failures of such energy initiatives.

Demand side energy management opportunities with DES

The results also showed that the energy prices of VES differs between different times of the day. In business-as-usual scenario, this difference was substantial where average day time power and lighting costs were 30- 50% cheaper compared to their night time costs. This happened because model selected different energy technologies for different times of the day. Such opportunities with DES can incentivize rural communities to shift their energy extensive activities to that time of the day where energy price is low. This can further encourage productive activities in the village, for example, it can encourage communities to start cottage industries or agricultural processing within the village for which they currently travel long distances and pay high costs. Consequently, this may further increase their opportunity cost of time thereby impacting their energy use pattern. For example, as the opportunity cost of time increase, it may impact the shadow prices of bio-energy based cooking energy technologies and the village model may then find it more profitable to use LPG rather than bioenergy-based cooking systems for communities. However, these dynamic effects are not captured in the model.

Cultural and behavioral aspects of communities and their impact on village energy system

During the field research, several local misconceptions were observed to be associated with biogas slurry and the biogas technology in general (as discussed in Chapter 2). The model considered a scenario where it was assumed that households value the importance of biogas slurry and it becomes a sellable commodity in the village. The effect of this assumption was observed in all the energy system components. Here, model chose biogas for meeting village's power and cooking energy needs, and it made shadow price of non-biogas-based power technologies significantly higher. The net VES cost was the cheapest in this scenario as VES generated revenues with slurry sale and moreover this scenario resulted in the lowest health costs, lowest carbon emissions and highest household revenues from the sale of bioenergy feedstocks. This analysis shows that if rural communities are made educated on the value of biogas slurry and it becomes a sellable commodity, it will lead to a very optimal VES benefitting VES entrepreneur who profits from low net energy system costs, as well as local communities which profit with reduced energy tariffs and external costs.

Government policies on decentralized energy technologies

The model also considered a scenario which assumed withdrawal of government subsidies from grid electricity. However, results showed that grid electricity remains to be the cheapest option for lighting, power and irrigation needs for the community as Indian grid electricity supply is primarily based on cheap coal power. However, battery storage (based on grid power) became too expensive and biomass gasifier lighting replaced it in the night time. The withdrawal of grid subsidies also substantially reduced the shadow prices of other irrigation systems, which opened avenues for other irrigation technologies such as solar water pumps etc. This withdrawal of grid electricity subsidies also opens an opportunity to divert such subsidies to renewable energy-based systems, and the same was also assessed by the model. Results showed that the capital subsidies benefit solar technologies more in comparsion to other technologies as solar system requires high upfront capital costs and comparatively low operational costs. Results indicated that with little capital subsidies, solar technology can win over the grid electricity for meeting day time power needs of the community, provided subsidies are withdrawn from the latter. Results also showed that the government subsidies on bio-energy technologies such as gasifier or biogas may not be fruitful, as these technologies compete for the bio-energy feedstocks with other energy systems and food security of communities. Due to this, it may happen that local enterprises first avails government subsidies on such bio-energy technologies, but these projects ultimately fail on ground if their interdependencies with other energy systems and food security are overlooked.

Cost of investment for the decentralized energy projects

The cost of investment is an important criterion for the development of decentralized energy systems (DES) because the target customers are poor households (which perceive high discount rates in making small investments) and potential financiers perceive DES as risky investments (due to their remote locations and newer technologies). The model considred a scenario with higher cost of investment, i.e. high discount rate. Results showed that high cost of investment (discount rate) reverses the benefits of capital subsidies to renewable energy systems. Improved financing such as soft loans for renewable energy-based DES initiatives could facilitate their widespread. Field research observed that while rural banks do provide soft agricultural loans to farmers, financing for renewable energy technologies is a new concept for the rural banks. However, lately government promoted "NABARD" financing scheme in rural Uttar Pradesh which provided soft loans to rural households on the purchase of solar home systems (SHSs). Prathma Bank is a rural Uttar Pradesh Bank which financed maximum number of SHSs under this scheme. As per the author's interview with the Chairman of Prathma Bank, the outcomes of this program were disastrous as a significant proportion of beneficiary households defaulted in loan repayment and it was difficult for Banks to deal with individual household beneficiary. The community-based energy systems could give more confidence to banks on such loan repayments, however literature and field research observed that previous community-based energy initiatives have been unsuccessful in India. Palit and Sarangi 2014 suggests that a combination of community and entrepreneurial approach could yield successful decentralized energy projects. This way, banks will also be more confident in financing the decentralized energy projects. Through capital subsidy and soft loan schemes, government should encourage decentralized energy projects which are based on entrepreneurial approach but also involve ownership from local communities.

While this chapter focused on the modelling of an optimal village energy system (VES), the next chapter will assess the impact of VES on the economy of its participating households.

CHAPTER 5

5. IMPACT OF VILLAGE ENERGY SYSTEM (VES) ON THE WELFARE OF ITS PARTICIPATING HOUSEHOLDS

5.1 Introduction

In the previous chapter, a village energy model was presented that identified an optimal energy system for a village community considering diverse energy sources & technologies (energy system), their interdependencies and linkages with food security. The model gave an optimal village energy system (VES) where village households contributed their energy resources to VES, received income for the same and received energy services at a certain tariff. However, the model lacks its interaction with the economy of agricultural household (participating in VES) as it is important to analyze the implications of such VES on the household welfare in general. As an example, consider a case (scenario-1), where the household divides its produced cattle dung for energy production (the limit it can offer to VES) and another part for its fertilizer needs. Now, it could happen that its allocation of cattle dung for energy production is not sufficient for meeting all its energy needs, and therefore it must procure a costly energy generation system for the remaining energy needs. There could also be another case (scenario-2) where the household could have instead purchased the entire fertilizer requirement from market and could have diverted all its cattle dung for cheap energy generation and scenario 2 could have led to improved household welfare compared to scenario 1. The interactions of village energy model and agricultural household's decision-making strategy therefore can help in understanding whether scenario-1 or scenario-2 is beneficial for the household. Essentially, this interaction can help in understanding the welfare implications of village energy system on the agricultural household and the same is the objective of this chapter. As discussed in the subsequent section, agricultural household model will be the suitable choice to model the interaction between VES and household and to analyze VES's welfare implication on the household. Section 5.2 presents the literature survey on the existing studies that have tried to analyze the welfare implication of decentralized energy systems on the households. Section 5.3 presents the conceptual framework that guides this research. Section 5.4 presents the mathematical model that simulates the interaction of VES and the household's economy. Data input and the model results are discussed in section 5.5. Section 5.6 concludes the chapter.

5.2 Literature survey

Decentralized energy and household's energy access have gained significant research focus in the recent years. Firstly, there is a rich literature dealing in the cost benefit analysis of energy technologies at the household level or at the village community level. However, most of these studies have looked at the energy supply-demand of the household/ community in isolation from its food production or utilization of natural resources for other purposes. For example, cattle dung which can be used for energy, is also an important farm input for agricultural production and diverting dung for energy production may impact the food production of the household. The low-cost energy system that does not consider its implication on other interlinked household activities such as food production, may not give the best energy system for the household. For instance, Rahman et al. 2014 models the electricity and thermal energy system for the Bangladeshi households using pre-selected energy technologies (limited to solar and modern bioenergy) and HOMER modeling software. It then performs the cost benefit analysis on the household by comparing the levelized cost of energy generation (model results) with the existing energy supply options of those households, ignoring that the bioenergy is also linked with food production. In the settings of rural Liberia, Alfaro and Miller (2014) reported that biomass and hydro based local decentralized power system gives more savings to households compared to local diesel based decentralized power system, again ignoring the spillover effects of bioenergy usage to other economic activities of the household. Bhandari et al. 2016, Kobayakawa and Kandpal 2014, Hafez and Bhattacharya 2012 are another similar studies that model energy systems for the households in isolation from the other interconnected aspects of the household. Herran and Nakata 2012, Patil et al. 2010, Chauhan and Saini 2016 utilize optimization techniques to model low-cost energy systems for the households utilizing more variety of energy technologies, but they also ignore the implications of such energy systems on the food production and other economic aspects of the households. For example, Herran and Nakata 2012 while modelling an energy system in a rural Colombian setting assumed that the entire crop residues produced by the communities can be diverted for energy production, but ignored the fact that such residues can also be used for livestock feed in the rural area. Deshmukh and Deshmukh 2009, Hiremath et al. 2010 are some other similar studies but they have also ignored the implication to household economics while modelling decentralized energy systems.

Secondly, there exist studies that have utilized economic models to analyses the impact of biofuel production on the livelihoods of households. For example, utilizing an economy wide CGE model for Ethiopia, Gebreegziabher et al. 2013 observed that the biofuel investment in Ethiopia can improve rural household's agricultural productivity as well as benefit urban households from returns to labor. Hausman et al. 2012 utilized a structural vector auto-regression model to frame a relationship between corn-based ethanol production and the corn price affecting the food production. It observed that corn-based ethanol production is positively associated with increase in corn price. Bryngelsson and Lindgren (2013) utilizes partial equilibrium model to explore long term effects of large scale introduction of bioenergy on land use and food prices on global scale. It observed that the large-scale introduction of bioenergy would raise the food prices. However, most of these studies focused on liquid biofuels and are macro level researches. There are also some model based studies at household level. Daioglou et al. (2012) introduced a simulation model to analyze possible future developments of residential energy use in 5 developing countries and observed that climate policies can slow down the modern energy transition amongst low income households. Hiremath et al. (2010) in the case of a village in India argued that the promoting decentralized energy systems, such as local biomass for producing biogas and electricity, increase incomes and reduce CO_2 emissions compared to other renewables, however the study missed to include bioenergy system interdependencies with food production and all other interrelated activities of the households.

Further, Djanibekov and Gaur 2016 argues that the existing studies on the topic lacks the analysis of distributional effects of modern renewable energy/ bio-energy development on diverse categories of households and they also fail to include heterogeneities within households. For example, there may be a case where in the current scenario, rich households in a village discards their crop residues and poor households utilize them for their livestock feed or energy use. However, if a village energy entrepreneur plan to use these crop residues for biomass gasifier or in any bio energy-based power project, then it may be beneficial for rich households but may produce a scarcity of fuel or livestock feed for poor households. This shall be the distribution effects of modern renewable energy development, which have always been ignored in the existing studies. Eckholm et al. 2010 argues that the different categories of households consider different discount rates in making energy related investment and behave differently to energy use. Utilizing regression techniques on the household survey data from Jiangxi province of China, Chen et al. 2006 observed that households that have higher non-agricultural work opportunities have lower dependency on traditional bioenergy sources due to higher opportunity cost of time. Djanibekov et al. 2016 quoting Isaac and van Vuuren, 2009 mentions that the poor households are less likely to adopt modern energy technologies in contrast to richer households. Utilizing country wide CGE in Ethiopian settings, Gebreegziabher et al. (2013) observed that the investment into biofuel sector directly impacts the welfare of rural poor households but also indirectly the urban households, confirming the heterogeneity amongst different categories of households. Moreover, household is also heterogenous within itself in terms of, for example, gender and age of the household members. For example, during the field research, it was observed that the households with more household females got more off farm work during rice cultivation as females are more agile and suitable for rice sowing, whereas household males were observed to be preferred for sugarcane cultivation which needs more strength during sowing and weeding of sugarcane. So, the household members differed in terms of productivities and hence wages. Similar influence of such intra household heterogeneity can be expected for household energy use. For example, several econometric studies in developing countries have indicated the importance of household females in the energy security of rural households and their influence in energy transition (Burke et al. 2015, Rahut D. B. et al. 2014).

Further, the impact of decentralized renewable energy system on the household's economy can also be influenced if the households which were previously acting individually, now decide to act collectively for the development of modern energy. For example, consider a case, where rich households have agricultural residue surplus and poor households can have labor surplus. When both category of households (with their individual household characteristics) participate in the village energy system, this can lead to positive or negative implications on different categories of households. There may be case where a modern energy intervention doesn't bring positive outcomes for a household, however, if the same household pools its resources along with several other households, it may bring positive outcome for the same household with the same modern energy intervention. There are several studies in the literature of agriculture economics which have analyzed the change in the net gains of farmers when they combine their resources for some crop production compared to their net gains when they acted individually (Liang and Hendrikse 2016, Gerichhausen et al. 2009, Djanibekov et al. 2015) and they found positive influence of this resource pooling on some households of specific economic category. However, there is no such study available that analyze the same phenomenon where farmers combine their resources for energy production. This impact of resource pooling may be of great interest in case of decentralized renewable energies which need comparatively greater investment which might not be affordable at individual household level.

The above discussions suggest that it is extremely important to formulate household's energy development strategies that address nexus aspects around them, while accounting for the heterogeneity within and amongst the households. Further, it is also important to understand the spillover effects of such energy development strategies from one household category to another. The nexus approach addresses such interdependencies between energy, food production, natural resources and other sectors, and gives a framework for analyzing the energy use of household (Mirzabaev et al. 2014, Bazilian et al. 2011, Hussey and Pittock, 2012, Rasul, 2014). For analyzing household's energy development under the Nexus framework, it is very important that the household's activities and their interconnections are understood. To address above modelling challenges, a micro level model is required that allows investigation of household's response to any policy and technology change. An agricultural household models that utilizes the interconnection between its different economic activities (own production, market purchase and consumption), is an apt choice to address the above required modelling issues. There exist some studies that have used agricultural household models to analyze the bioenergy-based economic decisions of households (e.g., Pattanayak et al. 2004, Chen et al. 2006, Djanibekov et al. 2013, Guta, 2014). However, Djanibekov et al. 2016 argues that most of these studies have focused on econometric estimations and missed the *ex-ante* impacts of possible policy and technological changes on rural households. Also, they missed to consider the heterogeneity within and among households and interconnected issues (ibid). Djanibekov and Gaur 2016 tried to close the gaps and developed an agricultural household model to understand the energy decisions of the households and the spillover effects amongst rich and poor category of households. However, there exist several decentralized energy technologies which are gaining immense popularities in rural areas but are unviable/ infeasible/ less efficient at the household level but are only feasible at community level such as biomass gasifier.

To fulfil the above discussed research gaps, an agricultural household model has been presented in this chapter that interacts with the village energy model (developed in the previous chapter) to understand the consequences of such village energy system adoption on the household's welfare. Further, this will also simulate welfare implications of energy system adoption on different category of households such as rich household (households with large land endowment) and poor households (households with less land endowment).

5.3 Conceptual Framework

Conceptual framework guiding the research is depicted in Figure 5.1. It has 3 depictions. Firstly, it shows the functioning of Agricultural Household Model (AHM) where production decisions of the household remain dependent on its consumption choices, where household is assumed to maximize utility from the consumption of agricultural staples, market goods & factors, energy consumption subject to its constraints on agricultural production, labor and resource endowment. This can also be explained by the equation below:

$$Y = wL^{o} + p_a q_a - (p_m C_m + p_c C_c + p_a C_a + p_{fw} C_{fw} + p_{cd} C_{cd} + p_{rd} C_{rd}) \qquad (5.1)$$

Where, Y is the income, L is the labor, w is the wage rate, q is the produce (agricultural), p is the price vector, C is the consumption of market good & factors, energy, agricultural staples etc. Thus, any changes in the right-hand side of the equation will impact the income of the household.

Secondly, figure 5.1 depicts the interaction between AHM and VES, which is implemented by considering 2 assumptions: 1) household can contribute its resources such as labor, bioenergy, land to VES for energy production and receive income from VES at a predefined rate, or it can also sell its bioenergy produce or labor to market or can use it for its own, 2) household has the choice to purchase energy services from VES by paying a predefined energy service price to VES, or it can buy commercial energy from market or it can utilize its own bioenergy. Contribution of land by household is not considered in this research. Any changes on the right-hand side (RHS) of equation 5.1, will have an impact on the income (welfare) of the household. These variables on RHS can be impacted by the VES such as energy prices for irrigation or cooking etc. So, as shown in figure 5.1, any intervention with the VES, will have an impact on household consumption and labor supply. For example, cheap irrigation energy from village energy system can encourage households to grow water extensive but profitable crops with direct consequences on the household. This will impact their household consumption of different commodities and labor supply.

The third depiction of this figure 5.1 is the distributional impacts of VES. Different categories of households such as poor household (HH1) and rich household (HH2) can be linked to this village energy system (VES) and VES may have different impacts on different categories of households. For example, crop residues from rich HHs (which was a trash for them), can now be used in the village energy system, providing cheap electricity to the entire village, benefitting even the poor households by the access to cheap and clean power. This can also have a negative impact because crop residues were earlier used by poor households for cooking and now if these are being used for power generation, then it can push these households to buy expensive cooking energy impacting their welfare.

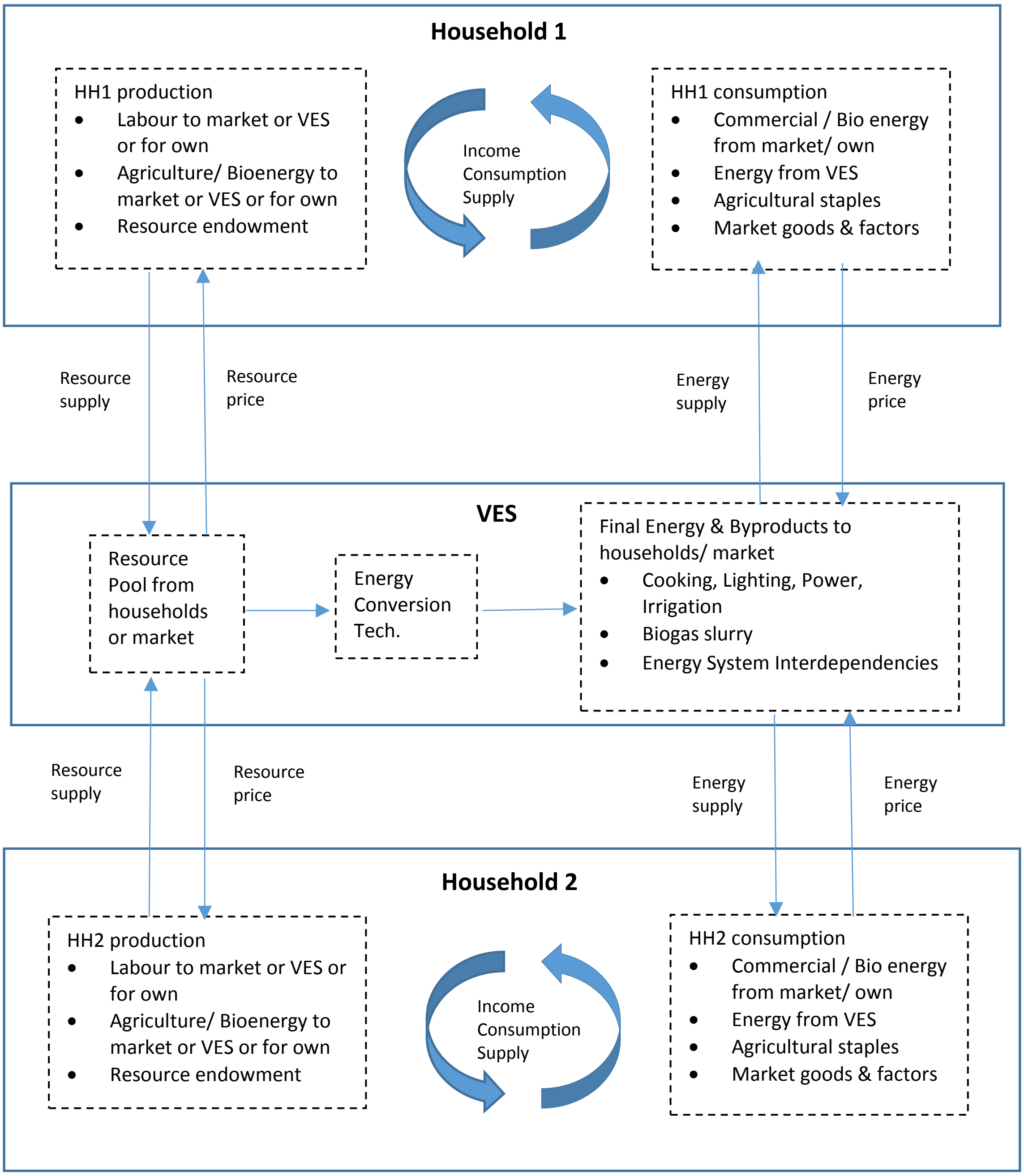

Figure 5.1: Conceptual Framework: Implications of VES on its participating households
Source: Author's own depiction

5.4 Agricultural Household Model linked with the Village Energy System (VES)

5.4.1 Mathematical representation of the model

In this section, an agricultural household model is developed which analyses the case that if household cooperates with the village energy system (VES), then how this interaction impacts household's welfare in terms of its income and external costs from energy system. Further it also analyzes VES's distributional impacts on different category of households. Following are the major assumptions/ characteristics of the model:

- It considers a situation where the VES enterprise proposes its participating contract to the village households (sharing of bio-energy feedstocks, prices of supplied energies etc.), and then the households (after considering the other energy options, its budget & its household economics) must decide whether to participate in the VES. As discussed in last chapter, some decentralized energy technologies used by VES (such as gasifiers) are long term investments and 15-year time horizon was considered while modeling the VES. Therefore, once installed, VES is not expected to be removed before 15 years. Participating household therefore has no choice to make intertemporal decisions and it must make a long-term decision now whether to cooperate with VES for 15 years or not? Therefore, a static agricultural model has been developed in this study to assess it's decision to participate in the VES in the very initial year.
- There is heterogeneity within household members. For instance, household men, women, children differ in terms of their productivities, labor hours available, wage rates, employment opportunities in agricultural and non-agricultural sectors.
- There is heterogeneity amongst households. There are 2 different category of households (rich and poor) which differ in terms of their farm land availability, endowment of agricultural equipments (which effects their respective agricultural input costs), livestock endowment, household budget availability, opportunities in non-agricultural employment (because of their different literacy levels), consumption patterns. In this model, these 2 categories of households are linked through this village energy system.
- It uses mixed integer programming, which allows the consideration that some of the model variables are constrained to be integers, while others could be fractional values. For example, sale and purchase of livestocks can only be integers while sale and purchase of livestock products can be fractions.
- Discount rates: These are the interest rates which are used to determine present value of future cash values. They not only consider time value of money but also the uncertainties of future cash flows. NSSO 2016 makes an analysis of the interest rates paid by Indian rural households in making their personal investments. Page 34 of this document mentions that the institutional lending agencies have been able to give credit to rural households in India with a moderate interest rate of 6% to 15%, but this could be substantially higher (even higher than 25%) with non-institutional lending agencies. Newspaper article by Iftikhar Gilani 2016 presents the government's recent initiatives in boosting institutional lending in rural areas, although in un-institutionalized lending, it also reports that poor rural households pay significantly higher interest rates. Assuming the

possibilities of personal investment by rural households as well as the possibilities of credit for making an energy investment, a discount rate of 14% is considered in this research. However, discount rates perceived by rich households may be different from the discount rates perceived by the poor households because of scarcity of cash in poor households as well as its marginalization to institutional lending. Using different publications that attempted to quantify discount rates faced by Indian rural households in making energy investments, Eckholm et al. 2010 observed that poor households perceive discount rate to be around 1.2 times higher than that perceived by rich households. However, because institutional lending has improved in last few years (NSSO 2016), rich households might have got more benefit in last years (Newspaper article by Iftikhar Gilani 2016) while poor household may continue to be marginalized from institutional lending, and therefore this ratio of 1.2 might further increase. Using the above argument, while this model assumes 14% discount rate for rich households, it assumes discount rate of 20% for poor households. This high discount rate for households will also cater to the case where due to budget constraints, household must take credit for making any investment for its personal energy system. For example, levelized cost of energy generation (lcoe) of solar water pump considering own investment with 14% discount rate will yield the same lcoe for the same investment through bank loan (including the loan repayment with 14% interest rate) and considering 10% discount rate.

The following section presents the mathematical representation of the model where the expected outcome of the system forms the objective function and the system characteristics & the behavior are modeled as constraints. The same set of following equations are used for modeling category 1 (poor household) and category-2 (rich household) of household, each of them interacting with the village energy system. These households differ in their characteristics and the input household data is discussed in section 5.4.2 and is given in Appendix 4 (table A4.1 (for poor household) and table A4.2 (for rich household)). The model is written in GAMS and is given in Appendix 5.

Objective Function of the model

The end objective of the model is the maximization of the annual household income (discounted annual net present value) over 15 years period, subject to constraints related to its budget, labor endowment, asset endowment etc. as discussed in this section. Farm household can derive its income from the sale of its agricultural crop output, sale of livestocks, livestock products, agricultural byproduct outputs, off-farm agricultural labor, off-farm non-agricultural labor such as salaried job, irregular non-agricultural job and business. The expenditure of the household includes input costs for crop production, purchase of agricultural products for family & livestock consumption, crop bioproducts for energy & livestock production , purchase of livestocks, livestock products, hired labor for the farms, purchase of cooking energy devices and the costs on cooking energy , purchase of lighting devices and the costs of lighting energy, purchase of power generation devices and the costs on power, purchase of irrigation devices and the costs on irrigation. While purchasing private energy production systems such as solar pump for irrigation or biogas for cooking etc, it also has an option to purchase energy services from the village energy system (VES) at given prices. The same is modeled in the objective equation. VES-household interaction is modeled in the income and expenditure sub equations of the objective function where household can earn income by selling its bio-energy to the village energy system and can incur expenditure with the purchase of energy services from the village energy system. VES-household interaction is also modeled in the subsequent constraint equations to limit the bio-energy resources for the household use after giving a share to the VES. The amount of bio-energy resource (such as crop residues or dung) that each household must give to village energy system for its operation was modeled in the VES (section 4.4.2), where it was calculated that what ratio of its produced bio-energy resources must be provided by household to the village energy system. The same is input here. Similarly, the VES 's energy generation costs were also simulated in section 4.4.2. Assuming VES will charge additional 30% to these energy generation costs (for the operation & maintenance and profits), the final VES energy prices are inputted to the AHM. Since, this model is required to be static in nature, therefore for investing in long term investments such as livestock purchase or purchase of personal energy systems, it utilizes their net present values and levelized costs of energy generation respectively over a period of 15 years, for which village energy system provides a contract. The following equation 5.2 presents the objective function for the model.

$$Max\ (AI) = Max\ (AR - AE) \tag{5.2}$$

Where, AI, AR and AE are annual income, revenue and expenditure of the household respectively.

Eq. 5.3 below models the annual revenue of the household considering all possible livelihood generation options for the household such as crops, livestocks, off farm labor, sale of bio-energy to village energy system (VES).

$$\begin{aligned} AR = {} & \sum_{i}^{5} CS_{\mathrm{i}} * cp_{\mathrm{i}} + \sum_{i}^{5}(\sum_{j}^{x} BS_{\mathrm{ij}} * bp_{\mathrm{ij}}) + \sum_{k}^{2} LS_{\mathrm{k}} * cL_{\mathrm{k}} + \sum_{k}^{2}(\sum_{l}^{2} LPS_{\mathrm{kl}} * lpp_{\mathrm{kl}}) + \sum_{m}^{3} ALO_{\mathrm{m}} \\ & * wA_{m} + \sum_{m}^{3} NLO_{\mathrm{m}} * wN_{m} + \sum_{i}^{5}(\sum_{j}^{x} CA_{\mathrm{i}} * CY_{\mathrm{i}} * rbp_{\mathrm{ij}} * bpmg_{\mathrm{ij}} * bp_{\mathrm{ij}}) \\ & + Wmx * Wmg * wp + Wsl * wp\_m + \sum_{k}^{2}(\sum_{l=2}^{2} nL * LY_{\mathrm{kl}} * lpmg_{\mathrm{kl}} * lpp_{\mathrm{kl}} \end{aligned} \tag{5.3}$$

Where,

- ❖ CS - agricultural crop output sold in a year (in Kgs),
- ❖ i: major crops (varies from 1 to 5: Wheat, Rice, Sugarcane, Mustard, Potato),
- ❖ cp: per unit price of crop output (Rs per kg). This is household (hh) data (section 5.4.2),
- ❖ BS: Byproduct output of each crop sold in a year (in kgs),
- ❖ j: Crop byproducts and x is their numbers per crop, for example: j=1 for wheat (wheat straw), j=1 to 2 for rice (rice straw & rice husk), j=1 to 2 for sugarcane (sugarcane dry leaves & sugarcane top), j=1 to 2 for mustard (mustard straw & mustard cake), j does not apply for potato,
- ❖ bp: per unit price of crop byproduct output (in Rs per kg). Table 5.1 presents the same,
- ❖ LS: number of livestock sold by household in a year (nos),
- ❖ k: livestock category (k=1 is buffalo and k=0 is cow),
- ❖ cL: price of the livestock (Rs per number). This is hh data (section 5.4.2),
- ❖ LPS: Livestock product outputs sold in a year (kgs),
- ❖ l: livestock product category (l=1 for milk and l=2 for manure),
- ❖ lpp: per unit price of the livestock products (Rs). This is hh data (section 5.4.2),
- ❖ ALO: Annual off-farm agricultural labor days worked (days per year),
- ❖ m: gender (1 =male, 2=female, 3=child),
- ❖ wA: Agricultural wage per day (Rs per day). This is hh data (section 5.4.2),
- ❖ NLO: Annual off farm non-agricultural labor days worked per year (days/ year),
- ❖ wN: Non-agricultural wage per day (Rs per day). This is hh data (section 5.4.2),
- ❖ CA: acres of crop grown per year (acres) for different crops,
- ❖ CY: Crop yield per acre per year (kg per acre). This is hh data (section 5.4.2),
- ❖ rbp: Ratio of crop byproducts to crop produce. This is given in Table 2.6,
- ❖ bpmg: percentage of annual crop byproduct transferred to the VES. This is discussed in section 5.5.1,
- ❖ Wmx: max annual amount of wood with household (kgs). This is the sum of wood that household spends on cooking and the amount sold in market. This is hh data (section 5.4.2),
- ❖ Wmg: percentage of household wood transferred to the VES. This is discussed in section 5.5.1,
- ❖ wp: wood sale price (per kg) to VES (Rs/ kg). Table 5.1 presents the same,
- ❖ Wsl: Annual amount of wood sold by household in market (kgs/ year),
- ❖ wp_m: market sale price of wood (Rs/ kg). Table 5.1 presents the same,
- ❖ nL: no. of livestocks at the end of year after sale & purchase of livestocks (nos),
- ❖ LY: Livestock yield (kg/ year). This is hh data (section 5.4.2),

- lpmg: Percentage of livestock product transferred to VES (for only l=2 i.e. manure), discussed in section 5.5.1.

Eq. 5.4 below models the annual expenditure of the household considering its expenses on crop production, livelihood rearing, market purchase of food commodities and energy commodities including purchase of energy services from village energy system.

$$AE = \sum_{i}^{5} CI_{\mathrm{i}} * CA_i + \sum_{i}^{5} CP_{\mathrm{i}} * cp_{\mathrm{i}} + \sum_{i}^{5}(\sum_{j}^{x} BP_{\mathrm{ij}} * bp_{\mathrm{ij}}) + \sum_{k}^{2} LP_{\mathrm{k}} * pcL_{\mathrm{k}} + \sum_{k}^{2}(\sum_{l}^{2} LPM_{\mathrm{kl}} * lpp_{\mathrm{kl}} + \sum_{m}^{3} ALI_{\mathrm{m}} * wA_m + \sum_{p}^{6}(\sum_{q}^{r}(\sum_{s}^{o} X_{\mathrm{pqs}} * Y_{\mathrm{pqs}})) + \sum_{p}^{6} EM_{\mathrm{p}} * pem_p + Wby * wp \quad (5.4)$$

Where,

- CI: Annual Input costs per acre for crop (Rs per acre). This is hh data (section 5.4.2),
- CP: Annual amount of crop output (for each crop) purchased from market in a year (kgs),
- BP: Annual Amount of crop byproducts purchased from the market per year (kgs),
- LP: number of livestocks purchased in a year (numbers),
- pcL: net present value of the livestock (Rs per number). This is hh data (section 5.4.2),
- LPM: Annual amount of livestock products purchased from market (kgs or ltr).
- ALI: Annual number of days of agricultural labor input in the farm (days per year).
- X_{pqs}: quantity of useful energy consumed (MJ) from energy system using energy resource s (with o number of energy resources), using energy conversion technology q (with r number of technologies), for end use energy application p (with 6 applications i.e. cooking, lighting in night, lighting in day, power in night, power in day and irrigation),
- Y_{pqs} - levelized cost of energy generation or purchase (Rs/ MJ) using combination of p,q and s. This is calculated using eq. 5.5, using energy technology data as given in Appendix 1. For the energy options based on bio-energy, input fuel costs are considered 0 unlike for VES where bio-energy sources were to be purchased from household. But here bioenergy is not purchased but self-produced and the time invested for the same has been considered in the subsequent equations.

$$Y_{pqs} = \frac{\sum_{t}^{T}\left(\frac{I_{pqst} + M_{pqst} + F_{pqst}}{(1+DR)^t}\right)}{\sum_{t}^{T}\left(\frac{E_{pqst}\left(1 - SD_{pqst}\right)^t}{(1+DR)^t}\right)} \quad (5.5)$$

Where,

- Y is the levelized cost of energy generation, I is investment expenditure, M is operations & maintenance expenses, F is fuel expenditure & E is Energy generation in time t, DR is Discount Rate (%), SD is system degradation rate (%), T is 15 years,
- EM: energy service purchased from the VES for different p (MJ or million lumen hours per year),
- pem: price of energy service purchased from VES. This is discussed in section 5.5.1,
- Wby: Annual amount of wood purchased by household from market (kgs).

Constraints of the model

The model uses the following set of constraints that represent the characteristics of the household and its conditions. The objective function is influenced by these set of household charateristics.

Budget constraint

Eq. 5.6 presents the budget constraint of the household that limits the possible annual possible expenditures of the household. Based on the household survey data, the budget of poor households is assumed to be Rs 50,000 and that of rich households to be Rs 1,50,000. This was calculated by subtracting annual revenues with the expenditures of the household (household survey data).

$$HB = \sum_{i}^{5} CI_{\mathrm{i}} * CA_i + \sum_{i}^{5} CP_{\mathrm{i}} * cp_{\mathrm{i}} + \sum_{i}^{5}(\sum_{j}^{x} BP_{\mathrm{ij}} * bp_{\mathrm{ij}}) + \sum_{k}^{2} LP_{\mathrm{k}} * pcL_{\mathrm{k}} + \sum_{k}^{2}(\sum_{l}^{2} LPM_{\mathrm{kl}} * lpp_{\mathrm{kl}} + \sum_{m}^{3} ALI_{\mathrm{m}} * wA_m + \sum_{p}^{6}(\sum_{q}^{r}(\sum_{s}^{o} X_{\mathrm{pqs}} * Y_{\mathrm{pqs}})) + \sum_{p}^{6} EM_{\mathrm{p}} * pem_p + Wby * wp \quad (5.6)$$

Where HB is annual household budget in INR.

Constraint on maximum non-agricultural labour with household

Eq. 5.7 limits the maximum availability of non-agricultural labour to household which may depend on the literacy level or gender or location etc of the household and its members (mNLO for m =1 to 3). This is hh data as discussed in section 5.4.2.

$$NLO_{\mathrm{m}} \leq mNLO_{\mathrm{m}} \quad (5.7)$$

Land constraint for household

This constraint limits the availability of agricultural land for the household in total and in different seasons of the year.

$$CA_i \leq mLD \quad (5.8)$$

$$CA_1 + CA_3 + CA_4 + CA_5 \leq mLD \quad (5.9)$$

$$CA_2 + CA_3 \leq mLD \quad (5.10)$$

Where, mLD is the maximum land area available with HH which is hh data as discussed in section 5.4.2; CA1 (wheat), CA4 (mustard) and CA5 (potato) are the areas of winter crops, whereas CA2 (rice) is the area of summer crop and CA3 is the area of sugarcane which grows throughout the year.

Labor constraint for the household

This constraint limits the total number of labor days available to the household member categories (m) for different purposes such as crop production(lcr), off farm agriculture (ALO), off-farm non-agriculture (NLO), livestock rearing(llr), bio energy production from crop residues(lber), firewood (lwer)and livestock products (ller); lh is the annual household labor days available for household member category (days) which is hh data as discussed in section 5.4.2.

$$\sum_{m}^{3}(\sum_{i}^{5} lcr_{\mathrm{im}}) + \sum_{m}^{3} ALO_{\mathrm{m}} + \sum_{m}^{3} NLO_{\mathrm{m}} + \sum_{m}^{3}(\sum_{k}^{2} llr_{\mathrm{mk}}) + \sum_{m}^{3}(\sum_{i}^{5}(\sum_{j}^{x} lber_{\mathrm{mij}})) + \sum_{m}^{3} ller_{\mathrm{m}} + \sum_{m}^{3} lwer_{\mathrm{m}} \leq \sum_{m}^{3} lh_{\mathrm{m}} \quad (5.11)$$

Constraint for household agricultural labor

This constraint utilizes the agricultural labor productivity of different household member categories to identify their respective labor participation in crop production.

$$\sum_{i}^{5} lci_{\mathrm{i}} * CA_i = \sum_{i}^{5}(\sum_{m}^{3}(lcr_{\mathrm{im}} * lcc_{\mathrm{mi}}) \quad (5.12)$$

Where,

- lci: annual male labor input requirement for each crop in days. In the hh surveys, labor requirement (male, female and child) for each crop was collected (section 5.4.2). Based on expert interviews, these were converted into male labor requirement per acre for each crop, as per the labor productivity ratios of males, females and children as described in lcc variable below.
- lcr: annual labor requirement for each crop categorized by household member category (male, female or child) in days.
- lcc: labor productivity conversion ratio for each crop for each household member category in comparison to household male. For rice crop, conversion ratio between female to male and child

to male is 0.8 and 0.5 respectively. This is because for sowing and weeding of rice crop, worker needs to be agile and females are more agile as compared to males. For sugarcane, these are 0.66 and 0.33 respectively. The productivities of females for sugarcane plantation is low because it requires strength in sowing, weeding and harvesting sugarcane as these are tall shrubs. For wheat crop, these were 0.8 and 0.5 respectively. These were 0.8 and 0.5 for mustard crop. For potato crop, these were 1.15 and 0.5 because of the similar reasons as discussed for rice crop.

Constraint for household livestock labor

This constraint utilizes the labor livestock labor productivity of different household member categories to identify their respective labor participation in livestock rearing.

$$\sum_{k}^{2} lli_{\mathrm{k}} * nL_{\mathrm{k}} = \sum_{k}^{2} (\sum_{m}^{3} (llr_{\mathrm{mk}} * llc_{\mathrm{mk}}) \tag{5.13}$$

$$\sum_{k}^{2} nL_{\mathrm{k}} = \sum_{k}^{2} (iL_{\mathrm{k}} - LS_{\mathrm{k}} + LP_{\mathrm{k}}) \tag{5.14}$$

Where,

- lli: annual male labor input requirement for each livestock category k in days. Based on the expert interviews in the field, this was around 70 male labor days per year per cow whereas for buffalo, it was 79. Buffalos need more labor because they eat more and are bigger then cows. The above information was on richer households. Rich households were observed to spend 20% more time compared to poor household because they rear costlier breeds.
- llc: labor productivity conversion ratio for livestock rearing for each hh member category in comparison to hh male. This is same for males & females, & for children it is 50% compared to males,
- iL: initial number of livestocks in each livestock category. Please refer section 5.4.2 (hh data),

Constraint for household labor for crop byproducts

This constraint utilizes the crop byproduct labor productivity of different household member categories to identify their respective labor participation in crop byproduct production.

$$\sum_{i}^{5} (\sum_{j}^{x} lbi_{\mathrm{ij}} * qb_{\mathrm{ij}} = \sum_{i}^{5} (\sum_{j}^{x} (\sum_{m}^{3} (lbr_{\mathrm{ijm}} * lbc_{\mathrm{ijm}}) \tag{5.15}$$

$$\sum_{i}^{5} (\sum_{j}^{x} qb_{\mathrm{ij}} = \sum_{i}^{5} (\sum_{j}^{x} CA_{\mathrm{i}} * CY_{\mathrm{i}} * rbp_{\mathrm{ij}} \tag{5.16}$$

Where,

- lbi: annual male labor input requirement for producing each kg of crop byproduct in days. For this, total amount of crop residues produced by the household (row 102 in table A4.1 and A4.2) is divided with its labor requirement (row 108 to 110 of Appendix A4.1 and Table A4.2) and is converted into male labor using labor productivity information from lbc.
- qb: quantity of crop byproducts produced in a year (kgs).
- lbc: labor productivity ratio for each crop byproduct (energy use) for each hh member category in comparison to hh male. As per field research, this is 1: 0.7 for male: female and 1:0.5 for male: child.

Constraint for household labor for livestock products that are used for energy

This constraint utilizes the labor productivity of different household member categories to identify their respective labor participation in production of the required energy from livestock products.

$$\left(\sum_{k}^{2}\left(\sum_{l=2}^{2} LDE_{\mathrm{kl}} * \mathrm{llei}\right)\right) = \sum_{m}^{3}\left(ller_{\mathrm{m}} * \ llec_{\mathrm{m}}\right) \tag{5.17}$$

Where,

- LDE: amount of dung which is used for energy production when l is 2 (kgs per year).
- llei: male labor input requirement for producing per unit of dung cake or biogas for energy generation (days/ kg or days/ m3). For this, total amount of dungcake produced by the household for energy (row 100 in table A4.1 and A4.2) is divided with its labor requirement (row 110 to 111 of table A4.1 and table A4.2) and is converted into male labor using productivity information (llec),
- ller: labor requirement for using dung for energy generation by each household member category,
- llec: labor productivity conversion ratio for using livestock dung for energy generation by each household member category in comparison to household male. As per field research, this is 1: 0.7 for male: female and 1:0.5 for male: child.

Constraint for household labor for fuelwood

This constraint utilizes the labor productivity information of household member categories to identify their respective labor participation in production of the firewood.

$$(\mathrm{Wen} + (\mathrm{Wmx} * \mathrm{Wmg})) * \mathrm{lwi} = \sum_{m}^{3}\left(lwr_{\mathrm{m}} * \ lwc_{\mathrm{m}}\right) \tag{5.18}$$

Where,

- Wen: Annual amount of wood which is used for energy production (kgs per year),

- lwi: male labor input requirement for producing per unit of firewood (days per kg). For this, total amount of wood produced by the household for energy (row 101 in table A4.1 and A4.2) was divided with its labor requirement (row 104 to 106 of table A4.1 and table A4.2) and is converted into male labor using labor productivity information (lwc),
- lwr: labor requirement for producing firewood (by each household member category),
- lwc: labor productivity ratio for producing firewood by each household member category in comparison to household male. As per field research, this is 1: 0.7 for male: female and 1:0.5 for male: child.

Constraint for household off-farm agricultural labor

This constraint limits the annual off farm agricultural labor of household to the maximum amount of household labor.

$$\mathrm{ALO_m} \leq \mathrm{lh_m} \tag{5.19}$$

Constraint for crop balance

This constraint makes sure that the crop production by household is equal to summation of crop products' sale (CS), own consumption (CC) & own consumption for livestocks (CL), and this is subtracted by its crop products purchase from market (CP). Further it limits that the crop sold cannot be more than the production, and the crop products purchased will be equal to sum of consumption and sale, and this is subtracted by production.

$$CA_{\mathrm{i}} * CY_{\mathrm{i}} = CS_{\mathrm{i}} + CC_{\mathrm{i}} + \sum_{k}^{2} (nL_{\mathrm{k}} * CL_{\mathrm{ki}}) - CP_{\mathrm{i}} \tag{5.20}$$

$$CA_{\mathrm{i}} * CY_{\mathrm{i}} \geq CS_{\mathrm{i}} \tag{5.21}$$

$$CP_{\mathrm{i}} = CS_{\mathrm{i}} + CC_{\mathrm{i}} + \sum_{k}^{2} (nL_{\mathrm{k}} * CL_{\mathrm{ki}}) - (CA_{\mathrm{i}} * CY_{\mathrm{i}}) \tag{5.22}$$

Constraint for crop byproduct balance

This constraint makes sure that the crop byproduct produced by household left after subtracting its amount supplied to VES is equal to summation of crop byproducts sold, consumption by livestocks (BL) and for energy purposes (BE), and this is subtracted by their amount purchased from market. Further it limits that the crop byproducts sold cannot be more than their amount left after supplying a portion to VES. The crop byproducts purchased by household will be equal to summation of their amount consumed by livestocks, energy production, sold in market, subtracted by amount produced and amount supplied to VES.

$$\sum_{i}^{5}(\sum_{j}^{x} CA_{\mathrm{i}} * CY_{i} * rbp_{\mathrm{ij}} * (1 - bpmg_{\mathrm{ij}}) = \sum_{i}^{5}(\sum_{j}^{x} BS_{\mathrm{ij}}) + \sum_{i}^{5}(\sum_{j}^{x}(\sum_{k}^{2} BL_{\mathrm{ijk}} * nL_{k})) + \sum_{i}^{5}(\sum_{j}^{x} BE_{\mathrm{ij}}) - \sum_{i}^{5}(\sum_{j}^{x} BP_{\mathrm{ij}}) \tag{5.23}$$

$$\sum_{i}^{5}(\sum_{j}^{x} CA_{\mathrm{i}} * CY_{i} * rbp_{\mathrm{ij}} * (1 - bpmg_{\mathrm{ij}}) \geq \sum_{i}^{5}(\sum_{j}^{x} BS_{\mathrm{ij}}) \tag{5.24}$$

$$BP_{\mathrm{ij}} = \sum_{i}^{5}(\sum_{j}^{x} BS_{\mathrm{ij}}) + \sum_{i}^{5}(\sum_{j}^{x}(\sum_{k}^{2} BL_{\mathrm{ijk}} * (nL_{\mathrm{k}})) + BE_{\mathrm{ij}} - \sum_{i}^{5}(\sum_{j}^{x} CA_{\mathrm{i}} * CY_{i} * rbp_{\mathrm{ij}} * (1 - bpmg_{\mathrm{ij}}) \tag{5.25}$$

<u>Constraint for wood balance</u>

This constraint makes sure that the wood produced by household left after its supply to VES is equal to summation of its market sale, own consumption for energy purposes and this is subtracted by wood purchased from market. Further it limits that the wood sold cannot be more than the wood produce of the household left after supplying a portion to VES. The wood purchased by household will be equal or less compared to wood consumed for energy.

$$\mathrm{Wmx} * (1 - \mathrm{Wmg}) = \mathrm{Wen} + \mathrm{Wsl} - \mathrm{Wpr} \tag{5.26a}$$

$$\mathrm{Wsl} \leq \mathrm{Wmx} * (1 - \mathrm{Wmg}) \tag{5.26b}$$

$$\mathrm{Wby} \leq Wen \tag{5.26c}$$

<u>Constraint for livestock balance</u>

This constraint makes sure that the livestocks sold by household cannot be more than the initial number of livestocks available to household.

$$\sum_{k}^{2} nL_{\mathrm{k}} \geq \sum_{k}^{2}(iL_{\mathrm{k}}) + LP_{\mathrm{k}} \tag{5.27}$$

$$\sum_{k}^{2} LS_{\mathrm{k}} \leq \sum_{k}^{2} iL_{\mathrm{k}} \tag{5.28}$$

Livestock product balance

This constraint makes sure that the livestock products (dung i.e. l=2) of household left after supplying a portion to VES is equal to summation of livestock products sold by household (LPS), own consumption (LHC), subtracted by their amount purchased from market (LPM). LHC is summation of LDE (amount of livestock manure used for energy (kg/ year)) and LDF (amount of livestock manure used for farm fertilizers (kg/ year)) where l=2. Further it limits that the livestock products sold cannot be more than the livestock products of the household left after supplying a portion to VES. The livestock products sold by household cannot be more than their amount left after supplying to VES.

$$\sum_{k}^{2}(\sum_{l}^{2} nL_{\mathrm{kl}} * LY_{\mathrm{kl}} \quad (1 - lpmg_{\mathrm{kl}}) = \sum_{k}^{2}(\sum_{l}^{2} LPS_{\mathrm{kl}} - \sum_{k}^{2}(\sum_{l}^{2} LPM_{\mathrm{kl}} + \sum_{k}^{2}(\sum_{l}^{2} LHC_{\mathrm{kl}} \tag{5.29}$$

$$\sum_{k}^{2}(\sum_{l=2}^{2} LHC_{\mathrm{kl}} = \sum_{k}^{2}(\sum_{l=2}^{2} LDE_{\mathrm{kl}} + \sum_{k}^{2}(\sum_{l=2}^{2} LDF_{\mathrm{kl}} \tag{5.30}$$

$$\sum_{k}^{2}(\sum_{l}^{2} nL_{\mathrm{kl}} * LY_{\mathrm{kl}} * (1 - lpmg_{\mathrm{kl}}) \geq \sum_{k}^{2}(\sum_{l=2}^{2} LPS_{\mathrm{kl}} \tag{5.31}$$

Constraint on the sale of livestock products also hold individually for respective livestock because for instance, the price of cow milk will be different than the price of buffalo milk. This is modeled in the equation below.

$$\sum_{k=1}^{1}(\sum_{l}^{2} nL_{\mathrm{kl}} * LY_{\mathrm{kl}} * (1 - lpmg_{\mathrm{kl}}) \geq \sum_{k=1}^{1}(\sum_{l}^{2} LPS_{\mathrm{kl}} \tag{5.32}$$

$$\sum_{k=2}^{2}(\sum_{l}^{2} nL_{\mathrm{kl}} * LY_{\mathrm{kl}} * (1 - lpmg_{\mathrm{kl}}) \geq \sum_{k=2}^{2}(\sum_{l}^{2} LPS_{\mathrm{kl}} \tag{5.33}$$

$$\sum_{k}^{2}(\sum_{l}^{2} LPM_{\mathrm{kl}} \leq \sum_{k}^{2}(\sum_{l}^{2} LHC_{\mathrm{kl}} \tag{5.34}$$

Resource constraint for the usage of dung for farm manure and the energy resources

Eq 5.35 below shows that the utilization of dung using different energy conversion techniques for different end use applications should not exceed the total amount of cattle dung which is annually available for energy purposes. Biogas slurry can also be used for farm fertilizer and is modeled in subsequent equations.

$$\sum_{p}^{6}(\sum_{q}^{o}(\sum_{s=r}^{r}(((X_{\mathrm{pqs}} * C_{\mathrm{pqs}})/(eff_{\mathrm{pqs}})/(ED_{\mathrm{pqs}})) \leq \sum_{k}^{2}(\sum_{l=2}^{2} LDE_{\mathrm{kl}} \tag{5.35}$$

Where, r is 1 which is dung, C is the conversion factor from usable form of energy to raw fuel which is "3" for dung cake to dung, and "25" for biogas to dung (Field research), eff is the efficiency of energy conversion device (Appendix 1), ED is the energy density of energy source (Appendix 1).

With the use of dung for biogas, slurry is formed and can again be reused as farm manure and the same is included in the model as follows:

$$TS = \sum_{q}^{0}(\sum_{s=1}^{1} X_{\mathrm{qs}} * S_{qs}) \tag{5.36}$$

Where, TS is the total slurry produced by biogas digester (kgs), s is 1 (dung), S is the amount of slurry produced per MJ of energy produced by biogas plant (associated with X_{qs}) and this is 1.97 kg/ MJ (Field Research and SNV 2011).

Eq. 5.37 below calculates the farm manure requirement associated with crop area cultivated. Further eq. 5.38 make sure that slurry output of biogas energy systems is also used as farm manure.

$$\sum_{i}^{5} CA_{\mathrm{i}} * MI_i = MR \tag{5.37}$$

$$MR = TS + \sum_{k}^{2}(\sum_{l=2}^{2} LDF_{\mathrm{kl}} \tag{5.38}$$

Where, MI is the annual farm manure requirement per acre of crop (kg per acre) which is hh data (section 5.4.2); MR is the annual farm manure requirement of household (kgs).

Resource constraint for crop residues for the use of energy

Equation 5.39 shows that the utilization of crop residues using different energy conversion techniques for different end use applications should not exceed the total amount of crop residues which is annually available for energy purposes.

$$\sum_{p}^{6}(\sum_{q}^{o}(\sum_{s=r}^{r}(((X_{\text{pqs}})/(eff_{\text{ pqs}})/(ED_{\text{pqs}}))\leq tcr \quad (5.39)$$

Where, tcr is the annual amount of crop residues available for energy (kgs), r is 2 (crop residues), o varies as (1=traditional cook-stove, 2=improved cook-stove, 6=gasifier-based light, 13= gasifier-based power).

$$tcr=\sum_{i}^{5}(\sum_{j}^{x}BE_{\text{ij}} \quad (5.40)$$

Resource constraint for the use of wood as energy source

Equation 5.41 shows that the utilization of wood using different energy conversion techniques for different end use applications should not exceed the total amount of wood which can be kept aside for energy purposes.

$$\sum_{p}^{1}(\sum_{q}^{o}(\sum_{s=r}^{r}(((X_{\text{pqs}})/(eff_{\text{ pqs}})/(ED_{\text{pqs}}))\leq \text{Wmx}\,(1-Wmg) \quad (5.41)$$

Where, s is 3 (wood), q varies as (1=traditional cook-stove, 2=improved cook-stove)

Energy demand Constraint

The purpose of these demand constraints is to make sure that there exists a combination of energy resources and their associated energy conversion technologies that fulfils the cooking energy demand of the household. Following equation models the cooking energy demand of the household.

$$CED=\sum_{q}^{o}(\sum_{s}^{r}X_{\text{qs}}) \quad (5.42)$$

Where,

- CED: annual cooking energy demand of the household. This is calculated using hh data (row 100 to 103 in table A4.1 and table A4.2 for poor and rich respectively). Energy feedstock consumptions are multiplied by their respective calorific values and efficiencies to calculate the total useful cooking energy used by household.
- o varies from 1 to 4 (traditional cook-stove=1, improved cook-stove=2, biogas cook-stove=3, LPG cook-stove=4)
- r varies from 1 to 4 (dung=1, crop residue=2, wood=3, LPG=4)

- ❖ Xqs = is the useful energy (MJ) provided by energy source s with energy conversion technology q.

The following equations model the lighting energy demand constraint in day time and in night time.

$$ledd = \sum_{s}^{r}(\sum_{q}^{o} X_{\mathrm{qs}}) \tag{5.43}$$

$$ledn = \sum_{s}^{r}(\sum_{q}^{o} X_{\mathrm{qs}}) \tag{5.44}$$

Where,

- ❖ ledn: annual lighting energy demand in night time. This is calculated using hh data (row 121 in table A4.1 and table A4.2 for poor and rich respectively). This was converted into lumen hours required by household in night by converting energy consumption to lumen hours production by respective lighting device (Appendix 1)
- ❖ ledd: annual lighting energy demand in day time, which is considered 0 (as per household surveys).
- ❖ r : 1= dung, 2= crop res, 3= wood, 5= kerosene, 6= solar, 7= diesel, 8=grid, 9= battery), o: 5= biogas mantle, 6= gasifier based light, 7=kerosene lamp , 7= solar light, 8= solar light with battery, 9= diesel genset based light, 10= electricity powered light, 11= electricity with battery powered light)

The following equations model the power demand constraint in day time and in night time.

$$pdd = \sum_{s}^{o}(\sum_{q}^{r} X_{\mathrm{qs}}) \tag{5.45}$$

$$pdn = \sum_{s}^{o}(\sum_{q}^{r} X_{\mathrm{qs}}) \tag{5.46}$$

Where:

- ❖ pdd: annual power demand in day time. This is hh data (row 123 in table A4.1 and table A4.2 for poor and rich respectively).
- ❖ pdn: annual power demand in night time. This is hh data (row 122 in table A4.1 and table A4.2 for poor and rich respectively).
- ❖ r: 1= dung, 2= crop res, 6= solar, 7= diesel, 8=grid, 9= battery), o: 12=biogas power, 14= solar power, 15=solar with battery power, 16= diesel power, 17= electricity grid-based power, electricity with battery-based power

The following equations model the irrigation energy demand constraint in day time and in night time.

$$\sum_{i}^{5} CA_{\mathrm{i}} * ied_{i} = \sum_{s}^{o} (\sum_{q}^{r} X_{\mathrm{qs}}) \quad (5.47)$$

Where,

- ied: annual irrigation energy demand of eah crop. Row 26-30 in table A4.1 and table A4.2 for poor and rich hh respectively. In the household surveys, information on the number of hours of irrigation per crop was received. Assuming 1-hour irrigation per liter of diesel and 35% diesel engine efficiency, useful irrigation energy per household was calculated.
- r: 6= solar, 7= diesel, 8=grid, o: 18= solar water pump, 19= electricity based tubewell, 20= diesel engine

Health costs associated with the use of energy system

The following equation models the health damage costs stemming out due to the usage of different energy sources (s) using different energy technologies (q) for different end use applications (p)

$$HC = \sum_{p}^{6} (\sum_{q}^{o} (\sum_{s}^{r} X_{\mathrm{pqs}} * hc_{\mathrm{pqs}})) \quad (5.48)$$

Where, HC is total health damage costs stemming out of the energy system, hc_{pqs} is the health damage costs associated with X_{pqs} (Appendix 1)

CO2 emissions associated with the use of energy system

Following equation models the carbon emissions stemming out due to the usage of different energy sources (s) using different energy technologies (o) for different end use applications (p)

$$CE = \sum_{p}^{6} (\sum_{q}^{o} (\sum_{s}^{r} X_{\mathrm{pqs}} * ce_{\mathrm{pqs}})) \quad (5.49)$$

Where, CE: total carbon emissions stemming out of the energy system, cepqs: carbon emissions (kgs) associated with Xpqs (Appendix 1).

5.4.2 Data for the model

Appendix table A4.1 and A4.2 presents the household data (descriptive statistics of the household characteristics as observed in the household surveys) that is used in the model. While A4.1 presents the data of poor households, table A4.2 presents the same for rich households. Tables start with household demographic information between row S. No 1 to 4. Household’s crop related information is presented between S. No 5 to 55 which includes information such as crop farm sizes, inputs, irrigation, labor requirement, yields, sale prices of crop produce. It is to be noted that data for 5 major crops has been used in the model and these include rice, wheat, sugarcane, mustard and potato. Data between S.No 56 to 78 gives the information on livestocks such as numbers, their consumption, market prices, yields, and market price of livestock products. This contains data on cow and buffalo as these were the most popular livestocks reared by the households. Data between S.No 79 to 97 presents information on annual off-farm labor of household males, females and children along with the wage rates. This includes off-farm agriculture and non-agriculture labor. S.No 98 to 121 presents the information on energy usage (cooking, lighting and electricity) of household such as consumption and requirement of different energy types along with their expenditures and labor spent on bio-energy collection. The subsequent table rows present the information on household consumption of food products (both own production and market purchase). The annual household revenues by the household is the last row of the table.

Table 5.1 below presents the prices of bioenergy fuels in Uttar Pradesh. Since these bioenergy prices differ in Western, Central and Eastern UP, their respective mean has been used here. It is to be noted that different sale and purchase prices have been considered for wood because households reported that when they go to local market for selling wood, then shop owner find excuses (such as thin wood logs, humid wood etc) to give lowest possible price for wood. But, when they go to purchase wood, then these are slightly thick wood logs and rates are fixed and high. To VES, households are expected to sell wood at a market purchase price as households would have greater negotiating power with VES.

Table 5.1: Bioenergy market prices observed by households

Bio-Energy fuels	**Price of fuels in local market (Rs/kg)**
Wood (household purchase price/ sale price to VES)	6
Wood (sale price in market)	1.5
Cattle Dung (Fresh)	0.5
Rice Husk	2.5
Rice Straw	0.9
Sugarcane dry leaves and sugarcane top (each)	0.5
Mustard straw	4
Source: Author’s own field surveys	

5.5 Results and discussions

This section utilizes the above developed household model to analyze that how the poor and rich household, respectively, make their household decision related to energy utilization, agricultural production and labor utilization in the business-as-usual (BAU) scenario. It will then explore that provided an opportunity to interact with VES, how the household activities and the net household welfare will be impacted, particularly its net income, its health damage costs and CO2 emissions from the energy system. The scenario analyzing the interaction of household with VES will be referred as VES scenario. Section 5.5.1 presents VES's energy service costs and its rules for participation by households. Section 5.5.2 presents the energy utilization pattern of poor and rich household in BAU versus VES scenarios. Section 5.5.3 and section 5.5.4 discuss the agriculture production pattern and labor utilization pattern, respectively of poor and rich households in different scenarios. Section 5.5.5 discusses the impacts of VES on the net household welfare.

5.5.1 Interaction of village energy system (VES) with households

This section presents the rules for the interaction between households and VES. It is to be noted that the characteristics of VES are different from that of household energy system because some technologies such as Biomass Gasifiers are not technically and financially viable for a single household, as discussed before. Further, the grid electricity supply for households and for commercial entities such as VES differ in terms of pricing (Appendix 1). As already discussed in the assumptions of model (Mathematical Model), discount rates of 14% and 20% have been considered for rich households and poor households respectively, while for VES it is 10%. This is because banks perceive loans to commercial entities less risky as compared to individual households, and moreover there are higher transaction costs dealing with individual households in comparison to VES. The discussion on discount rates was already made in the assumptions of model and in the last chapter. The interaction of VES and household model include the purchasing of bioenergy feedstocks by VES (from households) at predefined rates, which then provides energy services to households at certain tariffs.

As per the VES results for business-as-usual case (section 4.4.2), VES purchase the following percentage of household bio-energy resources:

- Rice husk:100% of household's produce @ Rs 2.5/ kg,
- Sugarcane dry leaves: 100% of household's produce @ Rs 0.5/ kg,
- Rice Straw: 62% of household's produce @ Rs 0.9/ kg,
- Cattle dung: 0% of household's produce @ Rs 0.5/ kg,
- Wood: 80 % of household's produce (in case of poor households) and 70 % in case of rich households. Wood is purchased at Rs 6/ kg.

VES offers different energy services to households in the following prices, including the 30% profit margin:

- Cooking Energy: 1.16 Rs/ MJ,
- Lighting Energy in night: 135.52 Rs/ million lumen hours,
- Power in day time: 1.57 Rs/ MJ,
- Power in night time: 2.23 Rs/ MJ,
- Irrigation Energy: 0.819 Rs/ MJ.

5.5.2 Energy utilization pattern of the households

This section presents the model results. It presents the cooking, lighting, power and irrigation energy utilization of poor and rich households in business-as-usual (BAU) scenario vis-a-vis the VES scenario.

a. Cooking energy utilization by the households in BAU and VES scenarios

Figure 5.2 below presents the cooking energy utilization pattern of the poor and rich household respectively in BAU vis-a-vis VES scenario. Figure 5.3 presents the shadow prices of utilization of different cooking energy technologies for both household types in both the scenarios. These figures are followed by discussions on the same.

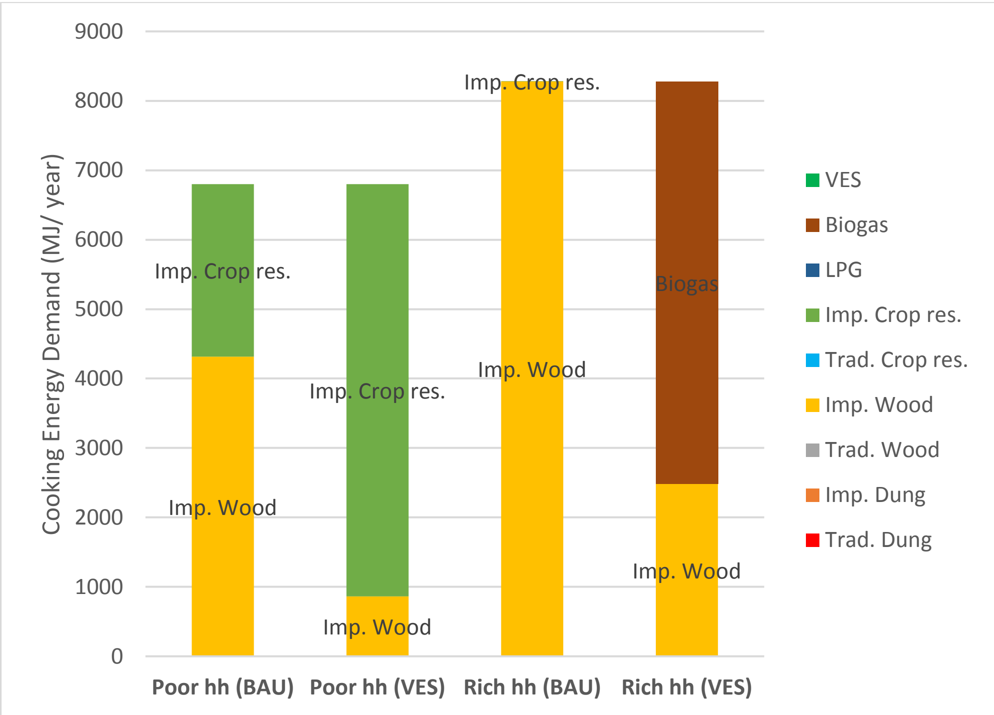

Figure 5.2: Cooking energy utilization by poor and rich household in different scenarios

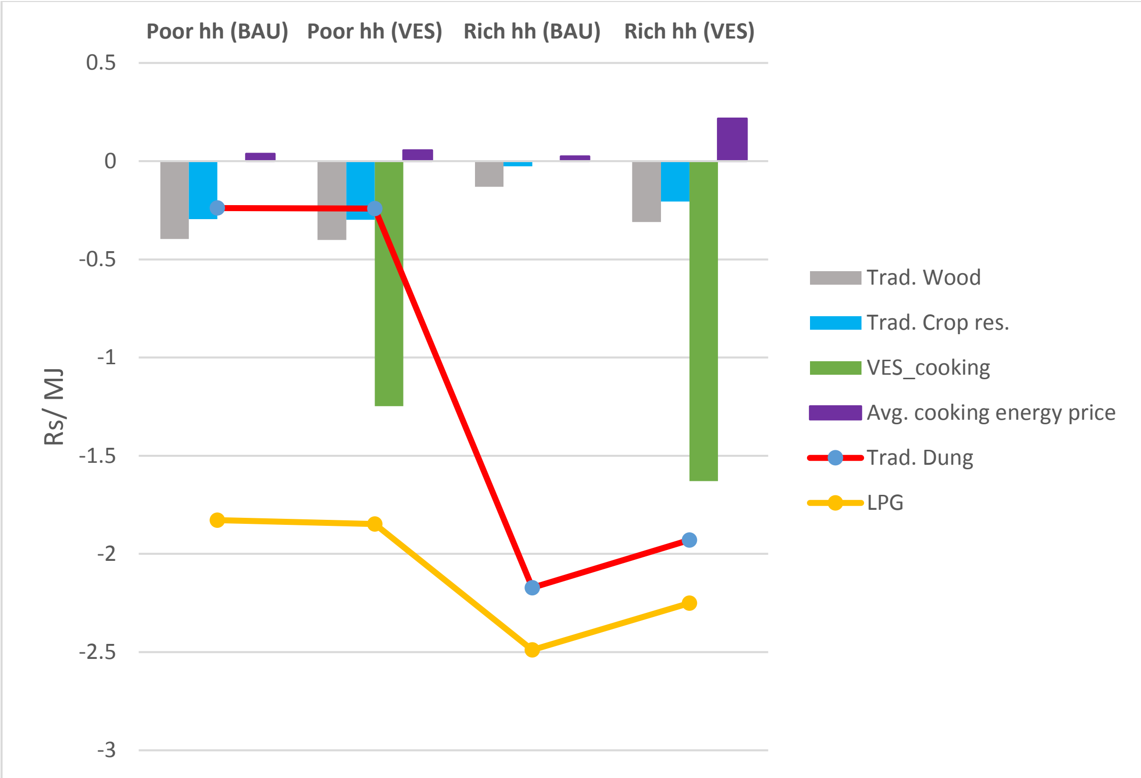

Figure 5.3: Shadow prices of different cooking energy technologies and average cooking energy price for poor and rich household in different scenarios

<u>BAU scenario: cooking energy for poor and rich household</u>

Figure 5.2 shows that in the BAU case, the poor household first uses firewood burnt in improved cook stove. However, the poor household has constraints with the availability of firewood, and in the time of its unavailability, it uses crop residues burnt in improved cook stove. The crop residues include sugarcane dry leaves and rice straw. Cooking energy utilization of rich household differ from the poor household with the fact that it has enough firewood for meeting its complete cooking energy demand with improved cookstove. Also, rich household's labor requirement per unit wood production is lower as compared to poor households as it has comparatively higher endowment of private trees (Appendix 4). There are 3 important things to note on this cooking energy utilization in BAU case. Firstly, the model results give high importance to the utilization of improved bioenergy cookstoves, however, during the field research, the same technology was observed to be absent. This was because of the lack of awareness on this technology. So, with increase in awareness of this technology and with its strong rural distribution network, households will find it beneficial to use this technology because of its significant thermal efficiencies and potential to save bioenergy which is increasingly becoming scarce in rural areas. Secondly, during the field research (as discussed in Chapter 2) households were observed to be using significant amount of cattle dung cakes along with firewood and crop residues whereas in these model results, cattle dung cake utilization is absent. The reasons for this are as

follows. It is true that calorific value of dung cake is lower than firewood and crop residues and that makes it less suitable in the model, however, it has a preferable property that it gives constant fire for long time unlike wood or crop residues which gives high instantaneous flame but extinguishes comparatively fast. For operating with wood and crop residues, household female needs to be present at the cookstove whereas using cattle dung cake requires less effort by woman as cattle dung flame is easy to regulate. In the field research, it was observed that household use a combination of firewood and dung cake for the cooking energy because dung cake regulates the flame of wood. This aspect is difficult to apply in the model and therefore model didn't yield dung cake as one of the preferred cooking fuel. Another reason could be that since households used traditional cook stoves, their wood consumption per unit of useful energy delivered was high, but wood being scarce, households had to use more dirtier energy source. Thirdly, the current model results do not suggest the LPG usage for cooking, whereas during the field research, rich households were observed to be using LPG. The reason could be that because of traditional bioenergy cookstove, household's bio-energy consumption per unit of useful energy delivered was high and since bio-energy is scarce, they had to look for alternatives such as LPG. Another reason could be that the model does not considers the cooking time taken by different cooking energy technologies as eating habits differ in different parts of Uttar Pradesh. This cooking time could be a significant factor for rich households who have household men doing white collared jobs and children studying in expensive schools. In such households, woman must cook food quickly and therefore rich household may prefer LPG or biogas in BAU case, however, model does not consider cooking time currently.

BAU scenario: shadow prices of utilization of different cooking energy technologies

Figure 5.3 presents the shadow prices of different cooking energy technology usage by different household categories in different scenarios. It has 4 major depictions. Firstly, it shows that the shadow price of traditional dung-based cooking is significantly higher for rich household compared to poor household, which means that it will be more expensive for rich household to utilize cattle dung cake based traditional cooking. One reason for this is the opportunity cost of time of the household. As shown in figure 5.4 below, the shadow price of inputting external farm labor for rich household is almost twice as compared to poor household. This means that if rich household must divert its farm labor to cattle dung cake preparation, then it will lose more money compared to poor household. Another reason is that rich households are net buyers of the cattle dung because of their large fertilizer requirements in their large farms, whereas, poor households have small farms and they have excess of dung which can be used for cooking or can be sold in the market.

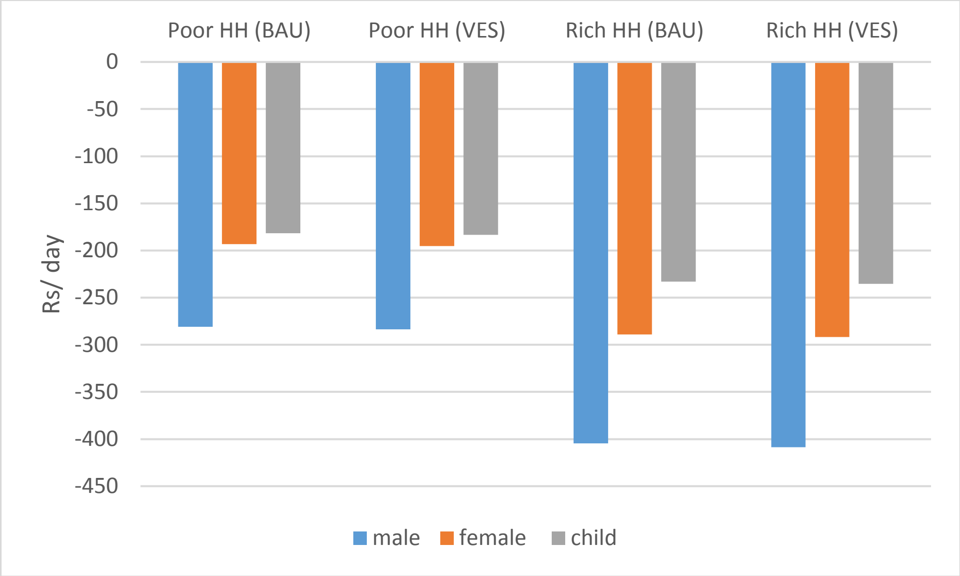

Figure 5.4: Shadow price of inputting external farm labor by poor and rich household in different scenarios

Secondly, the shadow price of LPG based cooking is comparatively higher for rich household compared to poor household. In the BAU, the average cost of cooking energy of rich household is almost 60% compared to that of poor household (see figure 5.3) as former has abundant private trees and therefore has lower levelized cost of cooking energy generation from improved wood stove. Due to this, replacing existing cooking energy with LPG based cooking will be costlier for the rich household. Thirdly, the shadow price of crop residue based improved cook stoves is significantly lower for rich household compared to poor household, because rich household has surplus crop residues whereas poor household already consumes all its crop residues either for energy (rice husk) or for livestock needs. Lastly, the shadow price of traditional wood-based cooking is significantly lower for rich household because it has abundant private trees and therefore household labor per unit of wood collection is significantly lower for rich household compared to poor household.

The major takeaway from these results is that the opportunity cost of time, and the abundance/ scarcity of household bioenergy supply significantly impact the household cooking energy utilization pattern.

<u>VES scenario: cooking energy for poor and rich households</u>

In the VES scenario, figure 5.2 shows that poor household does not prefers to purchase cooking energy from the VES and compared to BAU scenario, it now shifts to dirtier cooking energy, as discussed below. It first uses 20% of its wood endowment (left after its contribution to VES) for cooking, but rest of its cooking energy now comes from crop residues that it accesses from its limited stock and the remaining is purchased from market. This is because poor household can't substitute wood with wood because it has constraints on its free availability and its price in local market is high, whereas crop residues can be purchased from market at significantly lower price compared to wood. Regarding the purchase of crop residues from market, it is to be noted that the market of sugarcane residues (which is the cheapest fuel) is a local village phenomenon and once the VES operationalizes, there will be a crunch of this residue locally but other crop residues such as rice straw and rice husk are sold and purchased outside the village also, so village household will always have access to its market outside the village. This is the reason, crop residues emerge as the most important cooking energy source now. So, for cooking energy, it means that the poor household will make a transition to more dirty cooking fuel after its integration with VES.

In the BAU case, rich household was meeting its cooking energy requirement with wood based improved cook stove. While interacting with VES (VES scenario), rich household sells a certain portion of its firewood to VES at a predefined price which is higher than market sale price (discussed in section 5.4.2). While choosing an appropriate cooking energy system in VES scenario, instead of buying wood from market or using any other cooking energy system, rich household shifts to biogas because it has larger cattle endowment. By doing so, it can also use biogas slurry for its large farm fertilizer requirement. This also reduce its market purchase of dung for farm fertilizer requirement. This gives some monetary savings as well as significant reduction in health costs and CO2 emissions as biogas is cleaner fuel compared to wood based improved cook stoves. It is to be noted that if slurry utilization is not considered then the model might consider some other energy source such as dung cake or LPG or crop residues. It is to be noted that Biogas cooking could have also been an interesting technology for even poor household, but this technology requires capital costs and poor households perceive higher discount rates compared to rich households.

The results show that the integration to VES has different impacts on cooking energy utilization of rich and poor households. Large farm sizes, cattle endowment and therefore the opportunity to use biogas slurry in farms, make the rich household use biogas (more cleaner fuels) after it has sold most of its bioenergy feedstock (wood and crop residues) to VES. Whereas poor household now prefers to buy crop residues from market after it has sold most of its bioenergy to the VES, so it moves towards the dirtier cooking energy.

<u>VES scenario: shadow prices of utilization of different cooking energy technologies</u>

As depicted in figure 5.3, the shadow price for VES based cooking is slightly higher for rich household in comparison to poor household. This is because in VES scenario, rich household fulfils its major cooking energy need from biogas technology whose slurry output is used as farm fertilizer and this reduces the market dung purchase by rich household for farm fertilizers. So, the costs of biogas cooking has an associated benefit with biogas slurry. Therefore, any possible replacement of biogas cooking with VES cooking will also reduce the amount of slurry output from biogas, and this slightly increase the shadow price of VES cooking for rich household. The shadow prices of traditional bioenergy-based cooking (firewood and crop residues) for rich household increases in VES scenario compared to its BAU scenario. In BAU scenario, rich household had surplus wood and crop residues for cooking energy, however in VES scenario, it sold significant percentage of its wood and crop residues to VES. This creates a scarcity and for any further usage of wood and crop residues (low thermal efficiency of traditional cook stoves) and rich household now must purchase them from market and this increase their shadow price in VES scenario. However, there is almost no change in shadow price for poor household in VES scenario compared to BAU scenario. This is because in both the scenarios, poor household had limited bioenergy resources to be used for cooking energy production. For rich household, the shadow price of traditional dung-based cooking decreases in VES scenario compared to its BAU scenario. This is because that in VES scenario, rich household uses majorly biogas-based cooking which outputs biogas slurry and this is used as farm fertilizers and therefore the need for market dung purchase decreases compared to BAU scenario. Secondly, the average cooking energy price for rich households significantly increases in VES scenario compared to its BAU scenario and this also decreases the shadow price of traditional dung cake-based cooking for rich household. Similar justification can be given for the decrease of shadow price of LPG based cooking for rich household in VES case compared to its BAU case.

The results indicate that in the VES scenario, the shadow prices of other cooking energy technologies for poor household remain almost unaffected but for rich households, they become higher or remain high. This means that it will be costlier to replace biogas-based cooking for rich household in VES scenario.

b. Lighting Energy utilization of the household (Night time) in BAU and VES scenario

Figure 5.5 presents the model results for the night time lighting utilization by rich and poor household in different scenarios, while figure 5.6 presents the shadow prices of utilization of different lighting technologies for both the household types in both the scenarios.

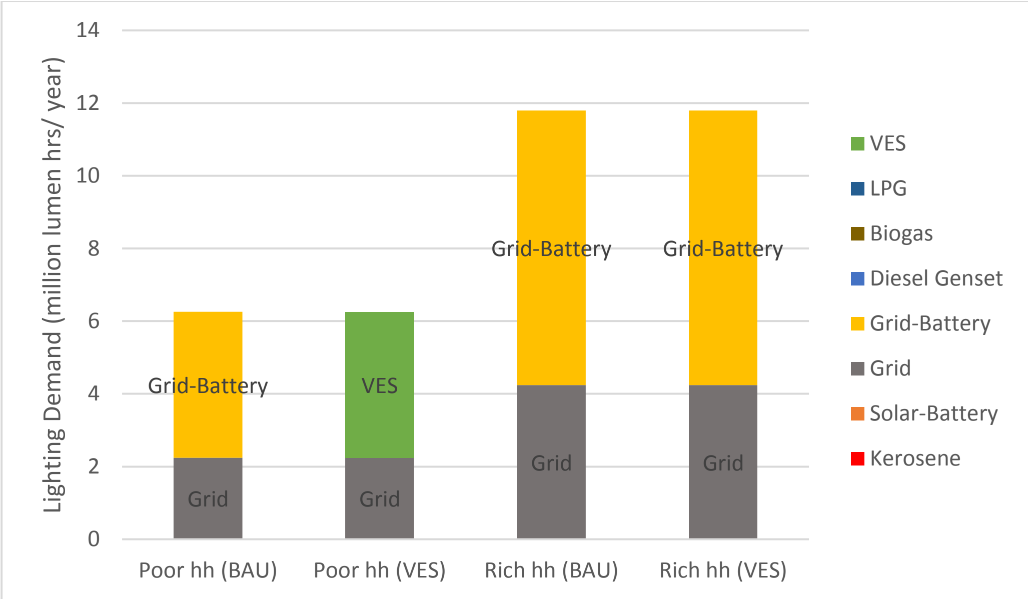

Figure 5.5: Lighting utilization by poor and rich household in different scenarios

<u>BAU scenario: Lighting utilization of poor and rich household</u>

For the poor household, model first chooses the grid electricity-based LED light, however, the grid electricity is not available throughout the day and night. So, when grid electricity is not available, it chooses the battery storage-based LED lighting (with stored grid electricity). Field research had similar observation for grid-based lighting where grid electricity is highly subsidized, although in several cases, households had illegal connection to electricity grid. At times of grid's unavailability, field research observed poor households using kerosene lighting which is a cheap lighting source but whose lumen output is low and lighting cost per million lumen hours is extremely high and therefore it is not chosen by this model. But field research noted that in the households with young men, even poor households had the increasing tendency to use small Chinese made cheap LED lanterns.

For the rich household, model first selects the grid electricity-based LED lighting, and when grid electricity is not available, it selects the battery storage-based lighting (with stored grid electricity). It differs with poor households in a way that the lighting energy demand of rich households is double that of poor households and therefore rich household uses larger battery bank compared to poor household for meeting its lighting energy need.

<u>VES scenario: Lighting utilization of poor and rich household</u>

For the poor household in VES scenario, model chooses the grid electricity-based lighting when it is available as it is highly subsidized. But when grid supply is unavailable, poor household now starts purchasing lighting services from VES, instead of using battery storage as was the case in BAU. Whereas, the rich household shows no change in their lighting pattern compared to BAU scenario.

This difference is primarily because that the investment in batteries requires high initial capital investment and compared to rich households, poor household experience higher discount rates in making such investments. Due to this reason, rich household prefer to make its own investment in batteries as its lighting demand is higher compared to poor household, whereas poor household purchase lighting from VES supply.

Shadow prices of utilizing lighting technologies in BAU versus VES scenario

Figure 5.6 below presents the shadow prices for utilizing different lighting technologies in different scenarios by both household types, along with the average lighting pricing. While the bar graphs are based on the left primary vertical axis, the line graphs (eg. For kerosene) are based on secondary right vertical axis. It shows that solar-battery based lighting technologies are costlier for poor households as compared to rich households. This is because solar-battery needs high initial capital cost and the model assumes high discount rates for poor households compared to rich households. For other technologies, particularly conventional technologies such as kerosene lamp, biogas lamp, the shadow prices are higher for rich household compared to poor households because the average lighting pricing for poor household is around 7-8% higher than for rich household. Comparing BAU scenario results, there are not much changes for both the households in VES scenario, except that the shadow price of solar-battery slightly increases for poor household in VES scenario, as the average pricing of lighting for poor household slightly decreases in VES scenario.

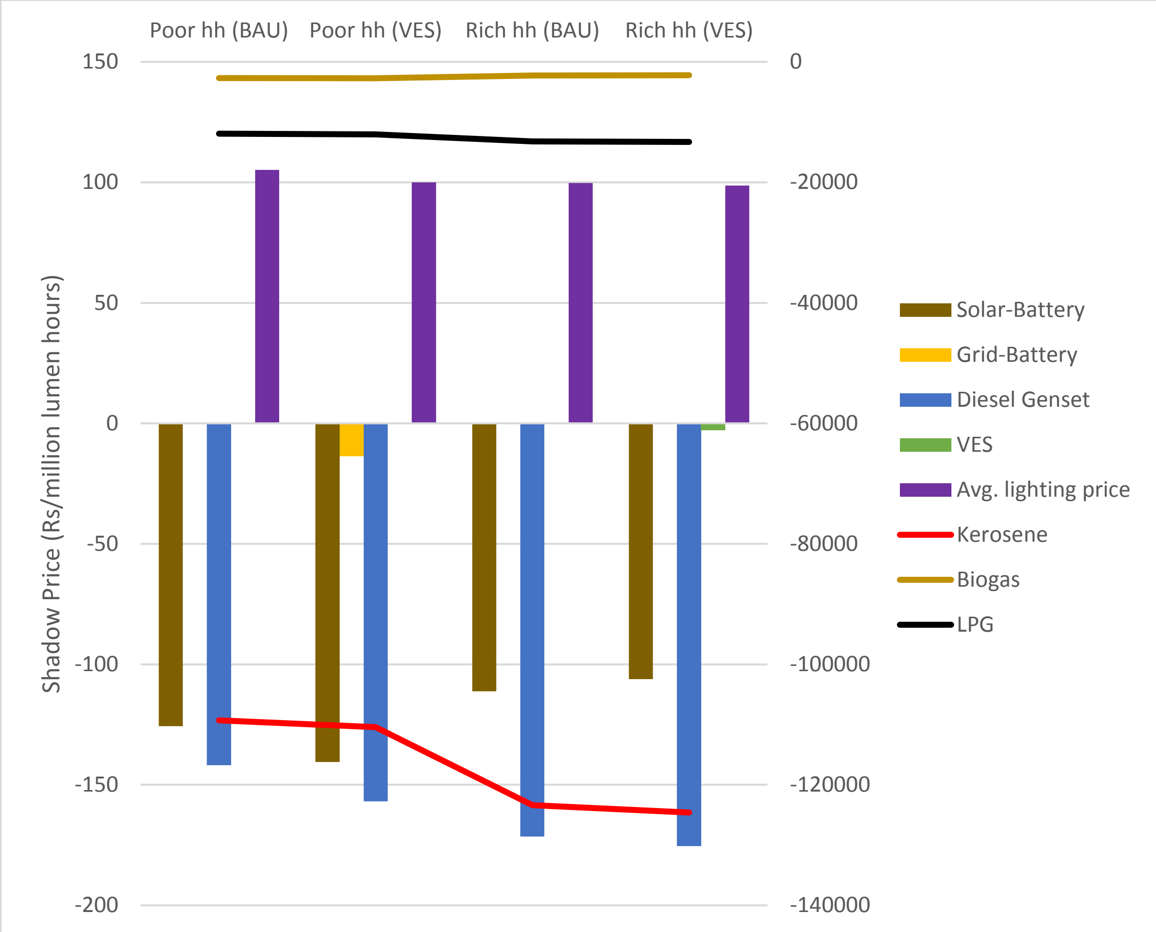

Figure 5.6: Shadow price of utilizing different lighting technologies and average lighting price for poor and rich household in different scenarios

Note: Bar graphs use left primary vertical axis and line graphs use right vertical axis

c. Night time power utilization by households in BAU and VES scenario

Figure 5.7 presents the model results for the night time power utilization pattern of poor and rich household in BAU as well as VES scenarios. Further, figure 5.8 presents the shadow prices of utilization of different power technologies for both household types in both the scenarios.

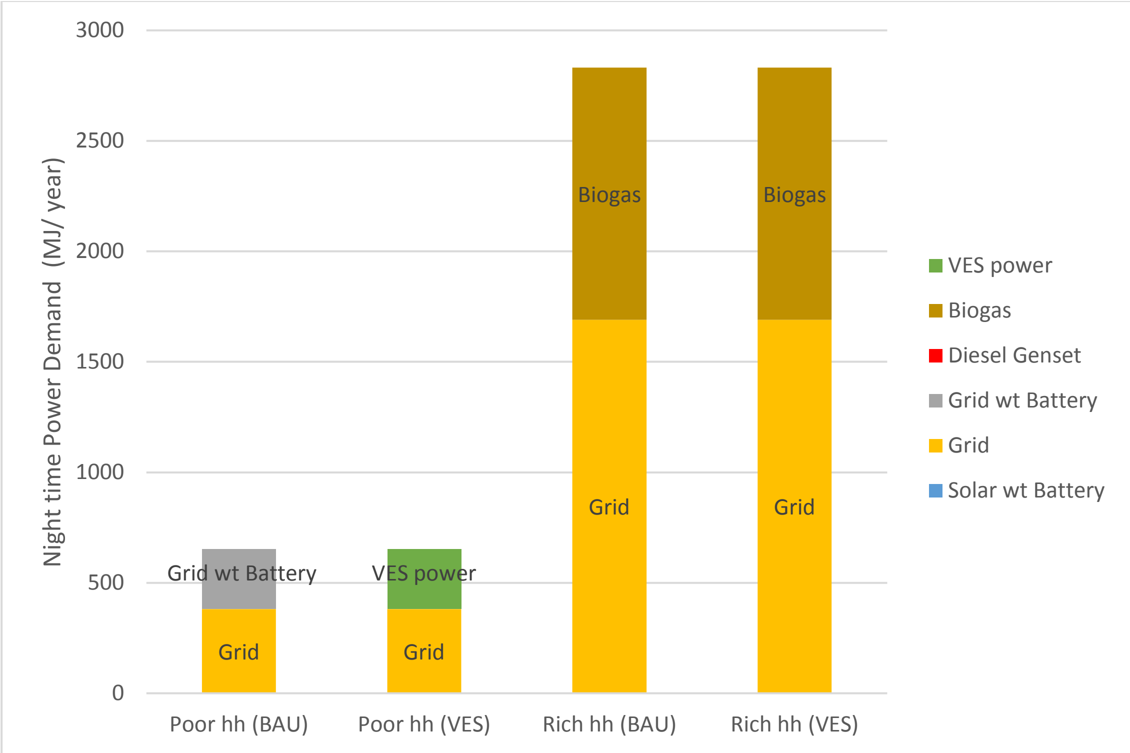

Figure 5.7: Night time power utilization by poor and rich household in different scenarios

<u>Night time power utilization by poor and rich household in BAU versus VES scenario</u>

For night time power applications in BAU scenario, model suggests that the poor as well as rich household choose grid electricity as it is highly subsidized. When grid electricity is not available model chooses battery storage (charged with grid electricity) for the poor household and biogas power for the rich household to meet its remaining power needs at night. Biogas power is more profitable for rich household because of its associated biogas slurry output which can be used in its comparatively large farms and its higher livestock availability in comparison to poor household. It is to be noted that Biogas power could not be an interesting technology for poor household because the gas engines used for generating biogas power are generally of higher capacities unlike conventional rural technologies such as diesel engine. Therefore, poor household who has comparatively lower power loads then rich household, is expected to have lower biogas engine efficiencies in comparison to that of rich household (model assumes 50% less efficiency for poor household in comparison to rich household) and therefore higher levelized cost of electricity in comparison to rich households. Technical reason for this low efficiency is that if lower loads are applied to the engines, then the engine's piston moves very fast and this leads to incomplete gas combustion and hence lower efficiencies and higher levelized cost of energy generation. In addition, biogas power requires higher capital investments and poor households perceive higher discount rates compared to rich households and this makes it costlier for poor household.

In the VES scenario, there is no change for the rich household, however, poor household now utilize VES power whenever grid power is unavailable. The reason is the high discount rates and budgetary constraints that poor households must consider while making own big investments, whereas rich households have larger budgetary and investment capabilities. Therefore, while rich households will find it cheaper to invest in their own power technologies, poor households will find their own investments expensive and will rather prefer to buy power from VES.

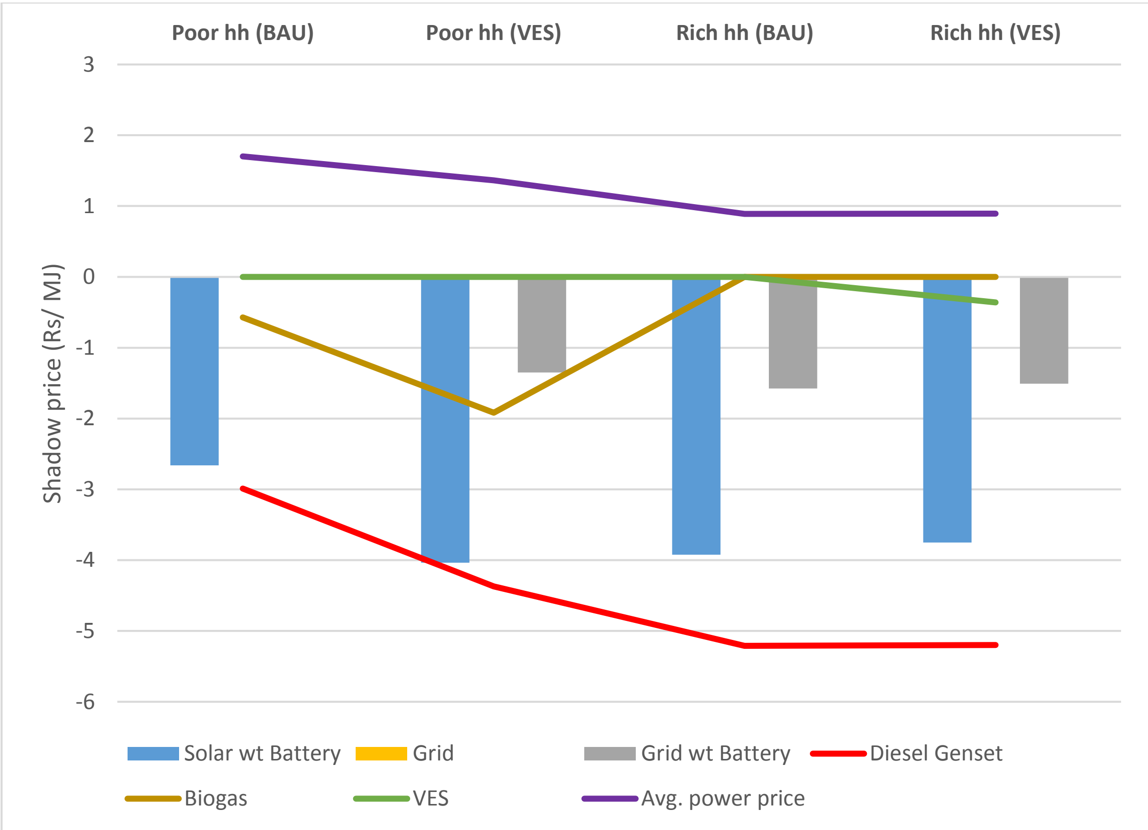

Figure 5.8: Shadow prices of power technologies utilization (in night time) for poor and rich household in different scenarios

<u>Shadow Prices for night power in BAU and VES scenario</u>

The shadow prices of all power technologies in night time in BAU scenario (figure 5.8) are higher for poor household in comparison to rich household. This is because the average power price for poor household in night time is higher compared to that of rich household due to higher discount rates for battery investment. In the VES scenario, while there is no change in the shadow price of power technologies for rich household, they increase for poor households. This is because the average power price decreases for poor household in VES scenario as VES night time power price is cheaper compared to the price that poor household was already paying in BAU scenario.

d. Day time power utilization by household in BAU and VES scenario

Figure 5.9 presents the model results for the day time power utilization pattern of poor and rich household in BAU versus VES scenarios. Further, figure 5.10 presents the shadow prices of different power technologies from the model which can be utilized in day time.

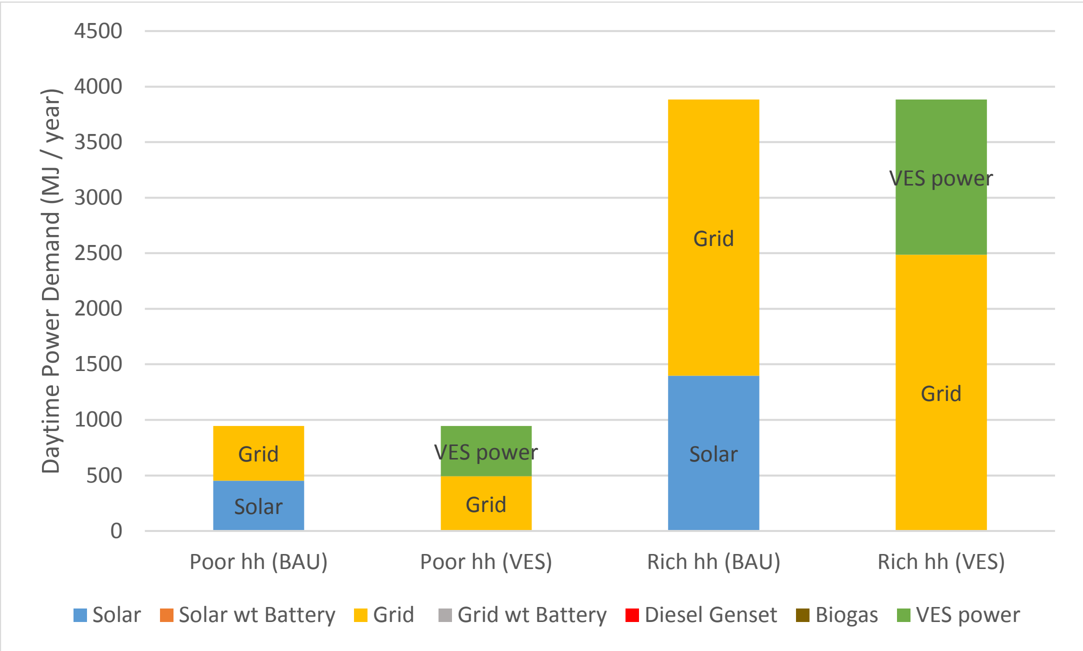

Figure 5.9: Daytime power utilization by poor and rich household in different scenarios

Day time power utilization by poor and rich household in BAU versus VES scenario

In the BAU scenario, model results show that both poor and rich household prefer to use grid power whenever it is available. When grid power is unavailable in day time, both will utilize solar power for meeting the remaining day time power requirements. With the rapidly decreasing solar technology prices, solar power is increasingly becoming an important technology for both centralized and decentralized power applications. Even in the field research, solar technology was observed to be gaining fast popularity amongst rural households, as discussed in Chapter 2.

In the VES scenario, both poor and rich household prefer to buy power from VES when their grid power supply is unavailable. This is because that the solar power requires high initial capital investments and because of their high discount rates considerations compared to VES (discussed in 5.5.1), both household find it profitable to buy power from VES, rather than investing in own solar capital.

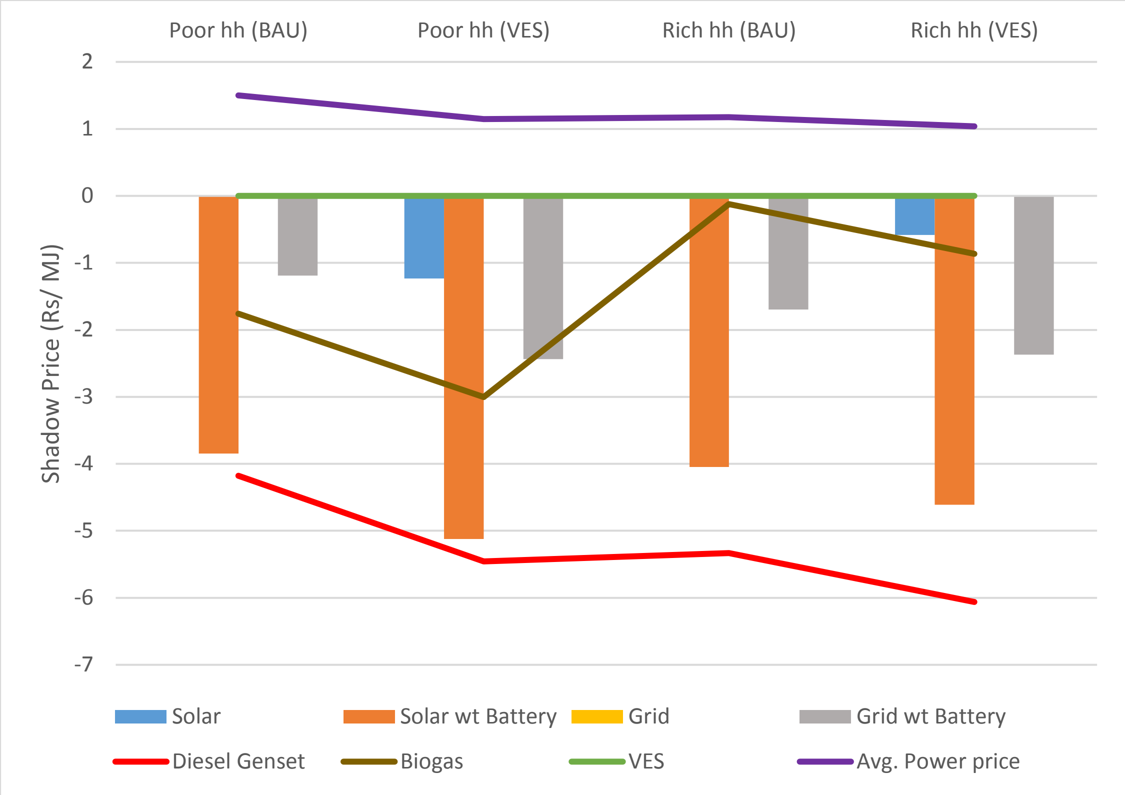

Figure 5.10: Shadow prices of power technologies utilization (in day time) for poor and rich household in different scenarios

<u>Shadow Prices of different power technologies in day time</u>

In the BAU scenario, shadow prices of all day time power technologies for rich household are higher as compared to poor households because the average power price for poor household is higher as compared to rich household. This is because of high discount rates considerations for poor households compared to rich households. These shadow prices mean that compared to poor household, it will be more expensive for rich household to replace solar power usage with any other power technology in day time. The shadow prices of all power technologies for both the households increase in VES in comparison to BAU scenario. This is because the average power price decreases for both the households in VES scenario as both households buy VES power in day time. However, the shadow price of solar power for poor household is almost 2 times that of rich household because of higher discount rate consideration for poor household.

e. Irrigation energy utilization by households in BAU and VES scenario

Figure 5.11 presents the model results of irrigation energy utilization pattern of poor and rich household in BAU versus VES scenarios. Further, figure 5.12 presents the shadow prices of different irrigation energy technologies from the model.

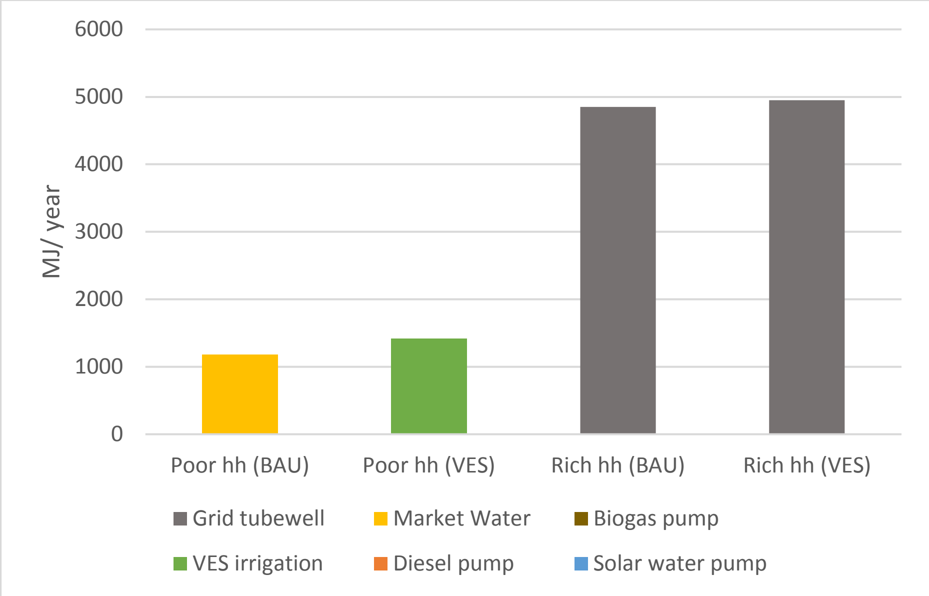

Figure 5.11: Irrigation energy utilization by poor and rich household in different scenarios

<u>BAU scenario: Irrigation energy utilization by rich and poor household</u>

In the BAU scenario, model suggests that the poor household purchases irrigation water from the village market to satisfy all its irrigation needs, whereas, rich household invests in its own grid tubewell for irrigation water. Similar phenomenon was also observed in the field research. There are 2 major reasons for the above. Grid electricity based tubewell is a difficult option for poor household because it requires lot of capital investment, bribe, social clout (in government departments) and setting up of personal electric poles/ wiring from transformer for which even no bank will give any credit to poor household. As discussed in the model assumptions, poor household experiences high discount rates for making such investments as compared to rich households and this increases the levelized cost for the poor household in making such investments. Secondly, poor household has almost 4 times smaller farm land as compared to rich households and therefore for the same capital, poor household will have less utilization of grid based tubewell (model assumes 25% tubewell utilization for poor household in comparison to rich household) and this increase the levelized cost of energy for poor household. Due to these reasons, poor households rather prefer to purchase irrigation water from village water markets. It is to be noted that during the field research, diesel-based irrigation pump was found to be very popular. However, the reason for its popularity was not its cost effectiveness but difficulties (great bureaucracy, administrative harassment and high initial investments) in getting tube well connection.

VES scenario: Irrigation energy utilization by rich and poor household

In the VES scenario, poor household purchase cheap irrigation water from VES because VES utilizes the electricity-based tube well and it also perceives lower discount rates in making such investments. However, rich household continues to use its own grid electricity based tubewell in VES scenario as households get subsidized electricity for agriculture and rich household can afford the initial costs of grid electricity-based tube well. On the other hand, VES don't get subsidized access to grid electricity for tube wells (Electricity subsidies to commercial entities are smaller compared to households) and that is why VES irrigation water is expensive for rich households.

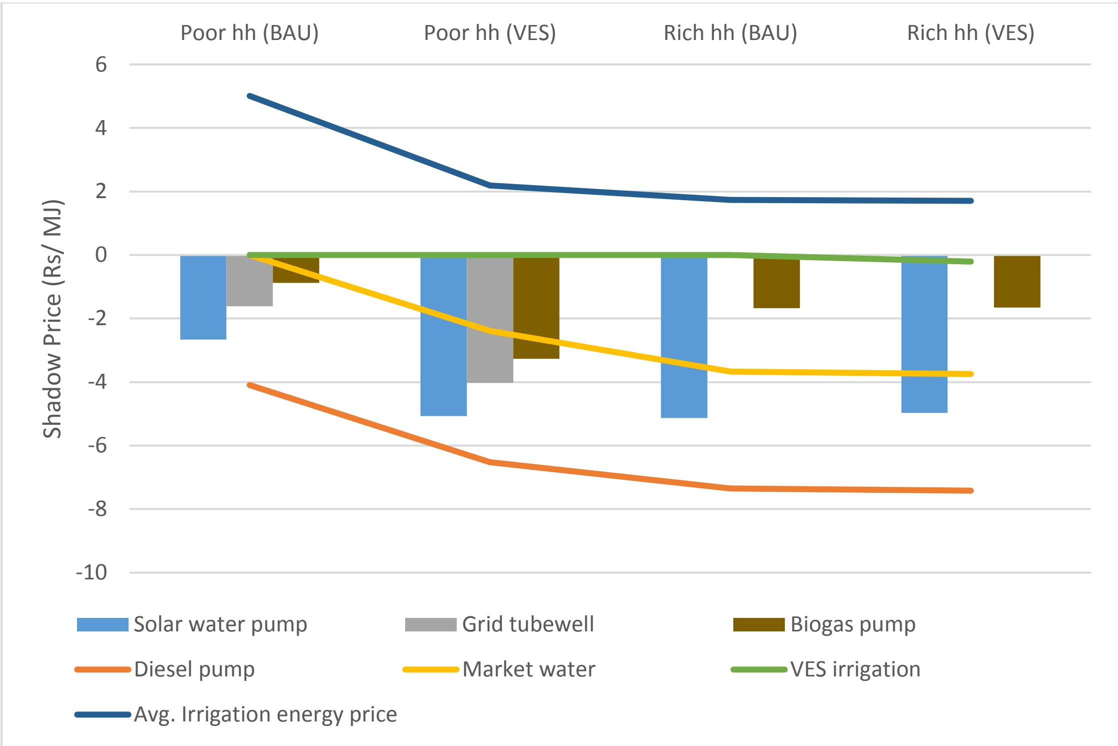

Figure 5.12: Shadow prices of irrigation energy technologies for poor and rich household in different scenarios

Shadow prices of irrigation energy technologies in BAU and VES scenario

The shadow prices of all irrigation technologies for rich household are expensive as compared to poor household because the average irrigation energy price for rich household is significantly lower compared to that of poor household in BAU scenario (as it buys expensive irrigation water from village market). Therefore, replacement of grid electricity-based irrigation with any other irrigation technology is expensive for rich household. Secondly and importantly, for poor household, the shadow price of biogas-based irrigation is cheaper as compared to grid based tubewell irrigation whereas for rich households, grid based tubewell is cheaper compared to biogas-based irrigation. This is because that the grid based tubewell needs high initial investment cost and fixed monthly fees irrespective of the energy units consumed. Therefore, if the farm is small and the utilization of energy is small, then grid-based irrigation will prove out to be costlier compared to other technologies. The shadow price of VES based irrigation for rich household is very small. This means that with slight increase in grid based tubewell costs, rich household can take the VES based irrigation.

5.5.3 Agricultural production of the households in BAU and VES scenario

This section presents model results that how the rich and poor household makes crop production decisions in BAU and VES scenario. Figure 5.13 below presents the model results on the major crops produced by the rich and poor household in BAU as well as VES scenarios. It is to be noted that Wheat, Mustard and Potato are winter crops in India, while rice is a summer crop. Sugarcane crop remains in the field throughout the year.

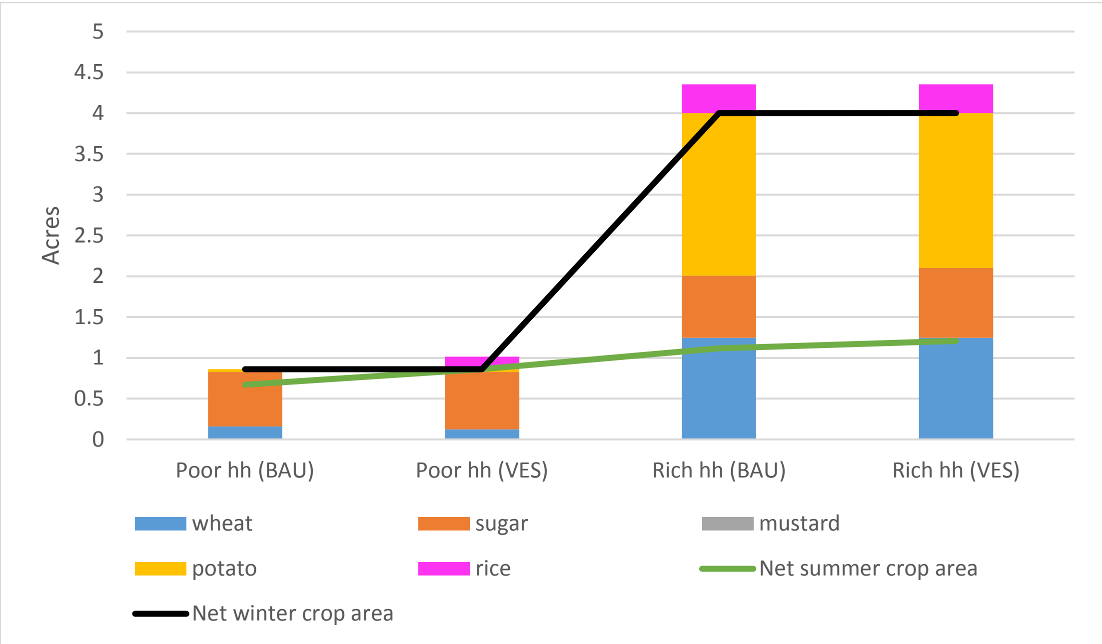

Figure 5.13: Crop production of the poor and rich household in different scenarios

<u>Crop production of poor and rich household in BAU scenario</u>

Figure 5.13 shows that the poor household in the BAU case prefers to grow sugarcane in around 78% of the farm area for self-consumption and for market sale. This crop remains in the field throughout the year and the remaining plot of around 22% area is left for other crops. In the winter season, it grows wheat and potato in the remaining plot for self-consumption, while in the summer season the remaining plot remains unused. Rice could have been a preferred crop for this vacant plot in summer season, however rice is a water intensive and a labor-intensive crop. Since poor household remain

dependent on the purchase of costly irrigation water from market (as discussed in Section 5.5.2 e), it keeps the remaining 22% farm uncultivated in summers and instead finds it profitable to divert farm labor to off-farm. In the field research, it was observed that household prefers to grow wheat and rice in majority of the farm area. This deviation of results could be because of the following reason. While, sugarcane crop is a profitable crop, poor household in practical scenario may find it risky to cultivate. This is because that with sugarcane, there is always an uncertainty in its market sales (price and purchaser) and since it requires lot of inputs, there is a higher risk involved in its cultivation. For example, during the household surveys, it was observed that sugarcane mills in Uttar Pradesh were buying the sugarcane from farmers, but were unable to make timely payments and there was a big back log of bills. Rich household can still wait for the pending payments, but this is a great difficulty for the poor households. In addition, growing wheat and rice gives a surety to the farmer that if there is a financial calamity in the family, there will be something to eat at home.

In comparison to poor household in BAU case, rich households prefer to grow potatoes in big part of the farm in Winters season. This crop requires high input costs and high manure inputs compared to other crops but is also a more profitable crop. Unlike poor households, rich household can afford high input costs and high manure inputs as they have higher livestock endowment, and therefore can grow potato in greater farm area. Further in winters, it grows wheat but for own family and livestock consumption. In summers, it grows rice crop for self-consumption. The reason for leaving around 3 acres of plot uncultivated in summers season by rich household is different than that of poor household. Since, rich household grows potatoes in big share of farm land in winters, it is unable to grow more sugarcane for which farm should be available throughout the year. Therefore, rich household is unable to grow more sugarcane and therefore has to keep around 3 acres of farm uncultivated in summers. Second reason is that in the modeling, only rice is the summer crop considered in addition to sugarcane, however, there could be other summer crops such as Millet which is grown in Western Uttar Pradesh along with wheat in winter season. This crop is not considered in the modeling work.

<u>Livestocks raised by rich and poor household in BAU scenario</u>

In the field research, it was observed that cows and buffalos were the major livestock categories reared by households, and therefore only these livestocks are considered in this study. The model output for BAU suggests that the poor household rear 1 cow (with child) and 1 buffalo (with child). This is like the observations of the field research. It is to be noted that the poor household's breed of cattle (yield, price and inputs costs) is comparatively lower quality as of rich households (Appendix 4).

For the rich household, the model output suggests that the household rear 1 cow (with child) and 2 buffaloes (with child). This is similar to the observations of the field research.

<u>Crop production of poor and rich household in VES scenario</u>

The figure 5.13 above presents the impact of VES on the agriculture pattern of poor household. In the BAU case, poor household used to leave around 22% of its plot empty in summer season because of expensive irrigation. However, in VES scenario, poor household is able to use the entire 100% land in summer for agriculture. This is because rice and sugarcane are water extensive crops and with the cheap irrigation water from the village energy system, the poor household is now able to grow rice and more sugarcane. Although the VES scenario had a very positive and significant impact on poor household's food production, it has absolutely no impact on the agricultural pattern of rich household, because it already had the access to cheap water from grid electricity based tubewell.

<u>Livestocks raised by rich and poor household in VES scenario</u>

Interaction with village energy system (VES) has no impact on the livestock raising of the household.

5.5.4 Household's labor utilization in BAU and VES scenarios

a. Farm labor

Fig. 5.14 and Fig. 5.15 presents the model results for household's annual labor utilization for own crop production and own livestock rearing respectively (for both poor as well as rich household in BAU and VES scenarios), followed by a discussion on the same. In this model, parameter "productivity of household male, female or children" was introduced to include different productivities of household member categories for different crops/ agricultural activity.

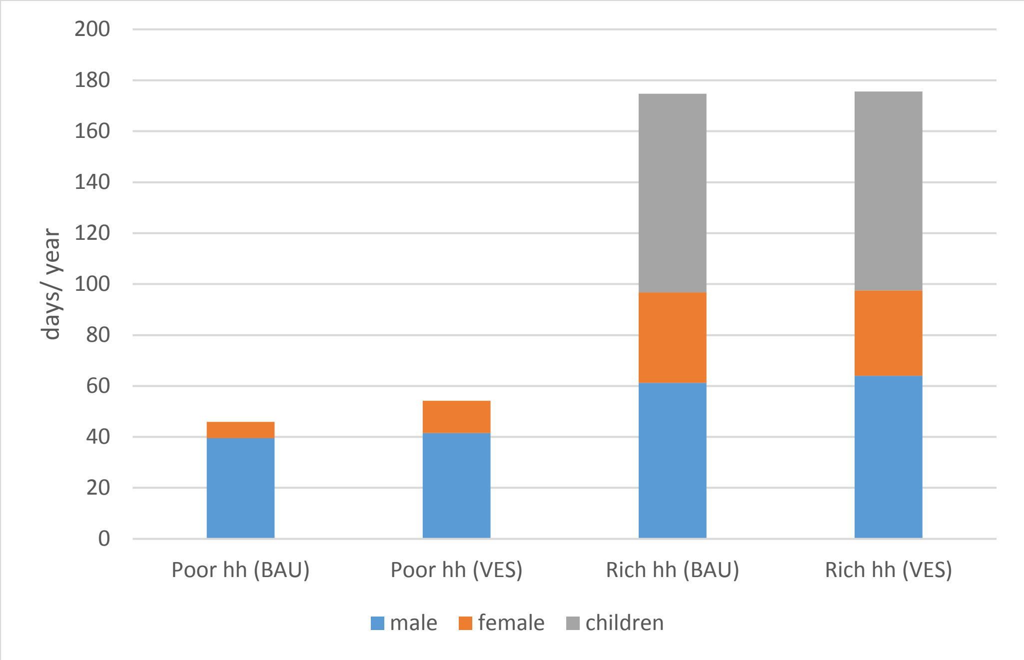

Figure 5.14: **Annual household labor usage for own crop production by poor and rich household in different scenarios**

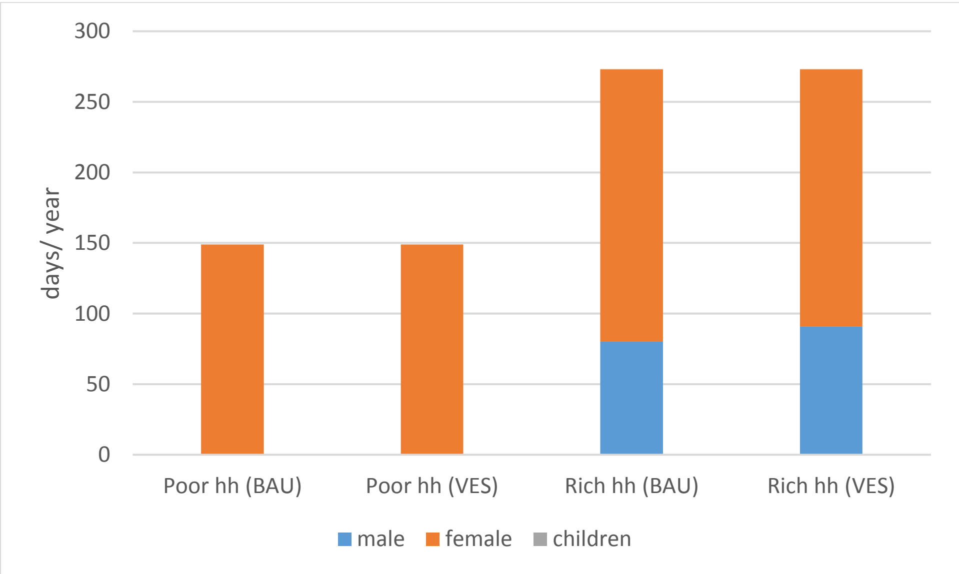

Figure 5.15: **Annual Household labor usage for livestock rearing by poor and rich household in different scenarios**

Annual household farm labor in BAU scenario

In BAU scenario, poor household mainly uses its household males for farm agriculture. This is because the household prefers to grow sugarcane crop which is a male labor-intensive crop unlike rice or potatoes. In sugarcane agriculture, it needs more strength in sowing, weeding and harvesting and is more suitable for males. The above result matches with the field research observation. On the other hand, poor household diverts its females for the livestock rearing. Similar phenomenon was also observed in the field research as livestock rearing don't require women to travel far away from home and it involves cleaning and feeding of livestock which don't requires high strength but agility. In the model output, household children don't spend time on own agriculture, however, in the subsequent section, it will be discussed that children are preferred to be spending more time on off-farm agriculture.

For the rich households in BAU scenario, model output shows the greater use of household children for the farming which is majorly due to potato cultivation. In the field research, it was observed that for the potato crop, children played a great role during its last stage where they pick potatoes from the field, sort them as per their sizes and put them in tractor storage. This task requires no greater strength and children with lesser wage rate can do it. Please note that the model has set a constraint that children of rich households don't do off-farm agriculture. This constraint is practical because households doing potato cultivation, exchange children labor for the last stage of potato cultivation where children from one household (hh x) help the neighbor household (hh y) in day 1 and in the next day children from hh y help the hhx because the entire work in 1 field must be completed in 1 day otherwise potatos will get destroyed in sun. So, the children don't do off-farm agricultural labor for wage but help each other's household, so, in a way they work on their own farm and this justifies 60 child labor days for agricultural household labor. Whereas household males prefer non-agricultural labor work due to its high labor wage rate. Rich household has more number of livestock, so it requires more labor. Model gives high share of this labor to the household female which also match the field observations as it gives the privilege to household female to work from home.

<u>Annual household farm labor in VES scenario</u>

This section analyzes the impact of household's interaction with VES on household's own labor utilization for own farm. For the poor household, it shows that household increases its time allocation to own crop production as its land area under crop production increases in this scenario because it can now grow rice with the cheap irrigation water from VES. Since, females have more productivity for rice production, as discussed in model assumption, the household females divert their time for rice production, rather than working in the farms of other households. However, there is no impact on the farm labor utilization of rich household for crop production.

b. Off-Farm Labor

Figure 5.16 below presents the model results for the household labor allocation for off farm agricultural labor (left vertical axis) and off farm nonagricultural labor (right vertical axis). This is presented for both poor and rich household in BAU scenario and in VES scenario.

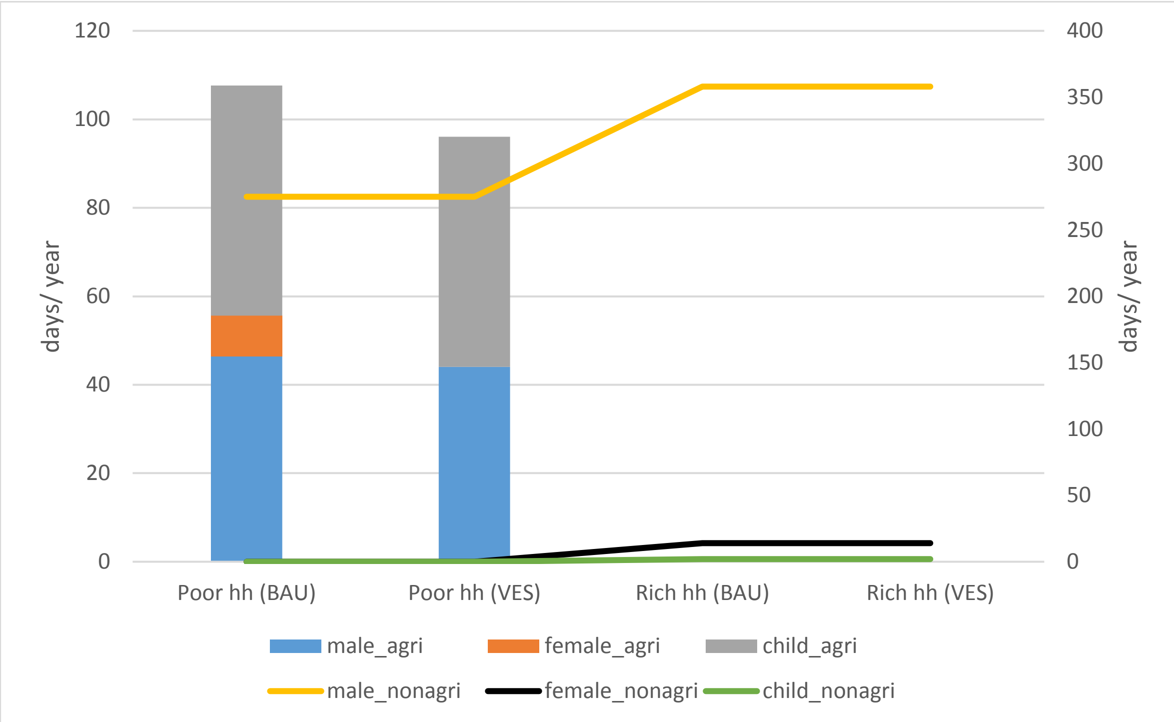

Figure 5.16: Household labor allocation for off-farm work by poor and rich household in different scenarios

Annual Off-farm labor for poor household in BAU

The results for non-agricultural labor matches the field research observations. For poor household, male off-farm non-agriculture labor has 20% high wage rate as compared to its male off-farm agriculture labor wage and this motivates poor household to divert most of its male labor on off-farm non-agricultural work subject to its maximum availability. Further, households associate it with learning new skills for livelihoods which may be useful for household male youths in future. There are almost negligible off-farm non-agricultural work opportunities for poor household females and children. One reason is that the poor household females are less educated compared to females of rich household. Secondly, the prevalent non-agriculture labor for poor households in and around village include brick kilns where females and children are not preferred. In addition, household hesitates in sending the household females and children to far off places as required for non-agriculture labor. There are some non-agriculture labor opportunities for household females and children near village such as school sweeper or house maid, but the wage rate is very low. For children, there exists non-agricultural work opportunities such as picking waste after the marriage functions etc but the wage rate is low. In addition, poor household females also get an opportunity to get some labor opportunity in MNAREGA (Mahatma Gandhi National Rural Employment Guarantee Act) program of government which provides some employment days to rural households (like building of canals, roads etc.) but here, contractors provide some small wage (compared to official wage) to household females in lieu of signature where household female get some money without even working and contractors take the rest wage amount. Therefore, households were reluctant in telling the work days they spent in MNAREGA program.

In the off-farm agricultural labor days category, model suggests household children to get the maximum share whereas household females get little off-farm labor days. The reason is as follows. In the field research of Eastern and Central Uttar Pradesh (poor regions), female wage rate was very low as there were small agricultural landholding. As there was surplus female labor for off-farm agriculture, children were not required for off-farm labor. Whereas in Western Uttar Pradesh districts, there were usage of children in off-farm labor for rice and potato but the wage rate of female and children were same (as picking potatos from field or sowing rice does not requires strength, so both categories were paid similarly). The above 2 reasons make average off-farm agricultural wage of children in the data set to be higher compared to household females. This makes model to choose children for off-farm agricultural labor while household males and females with more productivity are preferred for own agriculture.

Annual Off-farm labor for rich household in BAU

Model results for rich households also match the field research observations. For rich households, wage rate for non-agriculture labor is 100% higher than the average off-farm agricultural wage rate in the villages. This makes non-agricultural labor the most attractive livelihood opportunity for household males of rich household. Whereas for household female and household children, there exists not many opportunities for non-agricultural work as they hesitate in traveling away from home and females hesitate in doing MNAREGA job considering it as low stature job. As discussed in the case of poor household, there may be a case that rich household make their female sign her participation in MNAREGA work and get the undue wage without working (and contractor getting the remaining money) but they did not reveal that in the household interviews. The non-agricultural work opportunities for rich household females include teacher jobs but there are not many such opportunities in the villages. For children, this included distribution of pamphlets of some new shop etc, the opportunities for which are not widespread.

For the off-farm agriculture labor, the model put the constraint of zero work opportunities because as discussed in the previous "labor in own agriculture case" and "Hired labor case discussed next", where rich households exchange labor with the neighboring farm without wage.

Annual Hired labor by rich household for its agriculture in BAU case

The model output shows 0 hired labor for agriculture production. This does not match the field research observations, and this will not happen practically. This is because that there may be a case that rich household have enough labor to do most of the agricultural activities, but some agricultural activities are required to be done in 1 single day or in a short time such as sowing of rice otherwise water will go down, or, picking and sorting of potatoes after harvesting potatoes otherwise they will be destroyed in sun. Since, these activities must be done in 1 single day, household must hire outside labor. This phenomenon is not modeled but the assumption that rich household will share the household labor with neighbor farm will solve this problem. Here, for example, household needs 40 labors in single day, he will ask 3 neighboring households to support it the first day on the condition that he will send his 10 labor to 3 neighbors the subsequent days so that they can also finish work in 1 single day. So, in a way, he didn't hire any outside labor and his home labor compensated for the help of neighboring farmer.

Annual Off-farm agricultural and non-agricultural labor in VES scenario (for poor and rich households)

In the VES scenario, poor household reduces its annual off farm female agricultural days and divert it to own farm production as it increased its farm land under cultivation with the provision of cheap irrigation water from VES. Except for the change in poor household's off farm agriculture, no other change was observed in VES scenario in comparison to BAU scenario. For rich households, there is no impact in VES scenario.

c. Labor on energy production

This subsection present model results on the annual household labor utilization for its energy production. Figure 5.17 presents the same for both poor and rich household in BAU as well as VES scenario. This includes household labor spent on firewood collection, crop residue collection & processing, dung water mixture preparation for biogas plants.

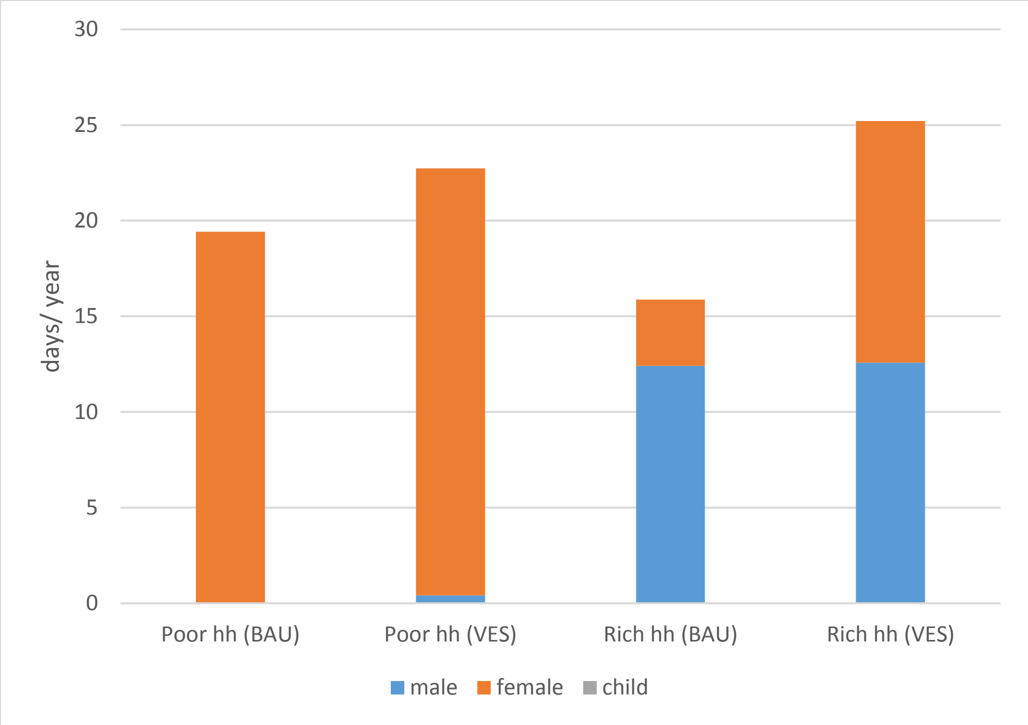

Figure 5.17: Household labor utilization for energy production by rich and poor household in different scenarios

Household labor utilization for energy production in BAU scenario

For the poor household, figure 5.17 shows that household females spend most of the time on energy utilization. For the rich household, the total labor spent is comparatively less and household males contribute significant time in energy production. Results for both rich and poor household matches the observations from the field. Rich household is majorly dependent on its private trees for firewood and its average labor spent on wood collection is significantly lower compared to poor household. The same is also the reason for rich household's larger male contribution in energy collection as male must climb its private trees and cut the thin branches carefully and bring back large amount of wood in one visit, where females and children play the role of helpers. However, poor household must search wood and collect little wood every day and this is majorly done by females and children who have more spare time. Secondly for dung cakes preparation, household females play a major role in both household categories.

Household labor utilization for energy production in VES scenario

In VES scenario, both poor and rich household increase their labor utilization for energy production. The reason is that both poor and rich household sell significant percentage of bioenergy to VES and therefore now must harness some more bioenergy which they were not harnessing in BAU scenario as it was not required. Secondly, the labor allocation of rich household on energy increases more in comparison to poor household because rich household now must harness biogas and its labor requirement per unit biogas energy is almost 3 times as compared to wood collection which was mainly from the private trees. Thirdly, both households increase the female labor allocation for energy. For poor household, this was achieved by diverting off-farm agricultural labor because bioenergy collection in this scenario also means money and off farm agricultural wage for poor household female is low. For rich household, this is achieved by diverting some female labor from livestock rearing because the labor productivity for both household male and female is same for livestock rearing as well as operating biogas, however livestock rearing is more profitable for rich household (as it has high breed cattles) and therefore male increase its time contribution in livestock rearing and females divert their time to biogas operation.

5.5.5 Household income and External Costs from energy system in BAU and VES scenarios

This section discusses the welfare impacts of village energy system (VES) on poor as well as rich household. This is measured by assessing the net income and the external costs for the poor and rich household in BAU as well as VES scenario. The external costs are measured by comparing the health costs (CO and TSP related) and CO2 emissions (in tonnes) from the usage of cooking, lighting, power and irrigation system. Appendix 1 discusses the health and CO2 emissions associated with energy technologies.

Table 5.2 below shows that for the poor household, with its interaction with VES, its household income increases by around 4%. This is not just because of household's savings in energy costs, but also because of VES's positive impact on its agriculture production where now it can grow crops in 22% more land in the summer season compared to BAU scenario. In addition, household also increases its revenue by the sale of its bio-energy resources to VES. However, figure 5.18 also shows that with its interaction with VES, poor household shifts to dirtier cooking energy sources such as crop residues and this results in associated increased health costs by 27% and around 45% increase in CO2 emissions compared to BAU scenario. The reasons for the shift to dirtier cooking technologies was already discussed in section 5.5.2.

Unlike the case of poor household, table 5.2 below, shows that VES don't have significant impact on rich household's annual revenues. This 0.9% increase is majorly because of the revenues it earns from the sale of bioenergy feedstocks to VES and the savings from the energy costs. However, in the VES scenario, rich household shifts to more cleaner cooking energy sources i.e biogas and this results in decrease in associated health costs by 54% and around 41% decrease in CO2 emissions compared to

BAU scenario. The reasons for the shift to dirtier cooking technologies was already discussed in section 5.5.2.

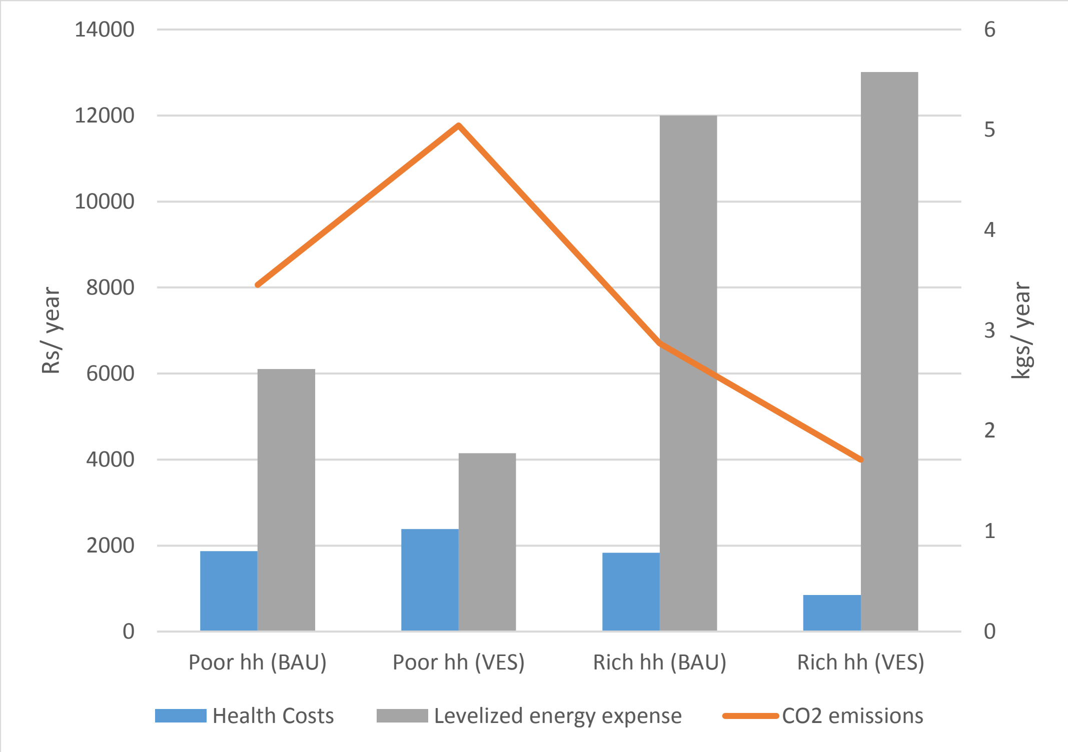

Figure 5.18: Health costs, CO2 emissions and levelized energy expense for rich and poor household in different scenarios

Table 5.2: Welfare impacts of VES on poor and rich household

Household category	Percentage Change in VES scenario vis-à-vis BAU scenario			
	Annual HH income	Annual energy expense (levelized)	Annual CO2 emissions	Annual Health Costs
Poor	3.6%	-32.09%	45.95%	27.71%
Rich	0.9%	8.40%	-40.38%	-53.78%

5.6 Conclusions and recommendations

The previous chapter modelled a village energy system (VES) for meeting the thermal, electrical, lighting and irrigation needs of a selected community, while considering all possible energy technologies and energy resources (energy systems), their interdependencies as well as their interlinkages with food security. The current chapter analyzed the impacts of VES on the welfare (economy) of its participating households, while considering the heterogeneities amongst and within the households. It utilized an agricultural household model (AHM) where household's production and consumption decisions are interlinked. The AHM was linked with VES (village energy model output) where household had the choice to purchase VES's energy services or buy commercial energy from market or utilize its bioenergy for self consumption. On the production side, household had the choice to sell its resources to VES or to the market or use it for self consumption. Research analyzed the distributional impacts of VES on both rich and poor household of the village. This subchapter presents the major research outcomes and the recommendations for the success of decentralized energy systems.

Distributional effects of Village Energy System (VES) on the village households

The results showed that VES makes different impacts on different categories of village households. VES's energy services proved to be more attractive for the poor household in comparison to the rich household as the former's budgetary constraint, lower energy demands, and high costs of investment (i.e. discount rate) make its personal investments on energy technologies more difficult. As a result, poor household intensified its energy utilization for agriculture. For the poor household, this interaction with VES led to its increased agricultural production with around 22% increase in farm area cultivation in summers, as well as led to reduction in its off-farm labor by around 11% which is then utilized in its own agriculture. Overall, this interaction resulted in around 4% increase in poor household's annual income. On the down side, this interaction led to poor household shifting towards dirtier cooking energy technologies resulting in increased external costs and CO2 emissions by around 27% and 45%, respectively. This happened because poor household found it profitable to sell its existing bio-energy resources such as wood to VES and instead use cheap bio-energy such as crop residues for its own cooking energy. On the other hand, VES did not impact rich household's food production and only marginally increased its economic gain. However, it led to rich household shifting towards cleaner cooking energy thereby resulting in reduction of its external costs almost by half. This happened because rich household found it profitable to sell its wood resources to VES and shift to biogas benefitting from its larger cattle endowment and the opportunity of using biogas slurry in its large farm. These results are of great practical significance because this explains that why some decentralized energy programs receive only partial success or benefit only certain categories of households. This can also be explained with an example below. Consider a biogas promotion program which is targeted for households with large number of cattles. There may be two subcategories of such households, one with larger farm areas and another with smaller farm areas. The production of biogas slurry (along with biogas production) can become an extra incentive for the households with larger farms. On the other hand, households with small farms may require extra resources to clear off the surplus biogas slurry which is very difficult to transport, leading to a disincentive. This shows that the same program could have different impacts on different categories of households. Therefore, energy development strategies should consider such heterogeneities amongst their target households and policies should be framed according to their individual characteristics.

Synergies and tradeoffs with decentralized energy systems

The results showed that decentralized energy systems could have synergies as well as tradeoffs for its participating households. For instance, while VES's interaction increased the farm area under cultivation for poor household, it also forced the same household to transition towards dirtier cooking energy technologies. Such tradeoffs and synergies existed for rich household as well, as discussed in the results. Therefore, energy development strategies should identify their synergies as well as their tradeoffs for the target households and should tackle the associated tradeoffs simultaneously. For instance, considering the current example of poor household which transitioned to dirtier cooking energy with its interaction with VES, such decentralized energy initiatives can also be combined with the subsidized cooking LPG scheme for the target households which don't interfere with the local resource pool of the households.

Sustainability of Decentralized Energy Initiavtes

For the long-term sustainability of any decentralized energy initiative, it is important to analyze its impact on the welfare of its participating households. This was proved with the model results where VES offered power, cooking, lighting and irrigation energy services to households, but agricultural household model chose not to buy cooking energy services from VES. This result has practical relevance. For instance, let us assume that there is a decentralized biomass gasifier project which purchase wood or crop residues form the village households and sell them electricity at affordable rates. Here, the participating households may benefit from cheap power supply, but for the same, they must give away some of their bioenergy feedstocks. This can further impact their household cooking energy supply or livestock feed. Such spillover effects can impact the sustainability of such decentralized energy projects and should not be overlooked.

Opportunities with improved bio-energy cook stoves

The results showed that the improved bio-energy cook stoves offer economic benefits to both types of the households. Compared to traditional bio-energy based cook-stoves, improved bio-energy cook stoves are more than two times energy efficient and produces significantly lower harmful gas emissions. With new advancements, they are also economically affordable now. Moreover, this type of cook stove matches local cultural preferences of the households as it give similar impression as cooking with traditional cook stoves, unlike gas-based cook stoves for which local households have several misconceptions. This technology has a great potential to save bio-energy which is increasingly becoming scarce in rural areas. However, it was observed during the field research that communities are unaware of this technology. Government should therefore undertake community awareness programs on this technology. In addition, its strong distributional network should be set up in rural areas.

CHAPTER 6

6. CONCLUSION OF THE RESEARCH

India faces an enormous energy poverty challenge with majority of its population dependent on unreliable, inefficient and polluting household energy sources such as traditional bioenergy for cooking and kerosene for lighting. Despite of several government efforts, the problem persists. Rural households make their energy decisions with respect to the Water-Energy-Food security (WEF) Nexus jointly, however, previous research initiatives have analyzed household energy access problem in isolation. Taking this WEF nexus into account, this thesis investigated factors influencing household energy transition and identified an optimal village energy system (VES) for the rural communities in Uttar Pradesh, India. The thesis also analyzed the distributional impacts of VES on different categories of rural households. For this analysis, household and village surveys were undertaken in Uttar Pradesh province of India.

Thesis utilized logit and zoib econometric techniques to analyze household's activities and to identify factors influencing household energy transition. The results showed that regular non-agricultural income of household's male member increases the probability of household's modern cooking energy and modern lighting transition by 8.6% and 13.6%, respectively. It was also found that household's higher agricultural dependence and resource endowments (more cattle and household labor) lead to higher share of traditional bioenergy consumption in its total cooking energy mix. It is therefore important to create synergies between household's agricultural production and its modern energy utilization. This can be done by identifying suitable energy systems that utilize local energy resources for modern energy production (decentralized energy systems) and creating value for the local household to participate in such energy system both as an energy feedstock supplier and a final energy consumer. Such an arrangement, while increasing household's paying capacity and the opportunity cost of time, can decrease its vulnerability to price shocks for food and energy, and make the DES's operations sustainable. Results also showed that household's proximity to markets (which signifies its higher opportunity cost of time) positively influence household modern cooking and lighting transition. Efforts should therefore be made to bring marginalized communities towards the center of development, such as through infrastructural developments (roads, employment schemes, education and entrepreneurial skills development, etc). It was also found that government's policy instrument such as household connection to government LPG scheme is associated with 20.5% increased probability of household using modern cooking energy as its primary cooking fuel. However, research also identified several barriers, such as high connection cost, that households face in getting the LPG

PDS scheme connection. So, government's policy instruments could have positive impact, but they should be strengthened in a way that even the most backward and marginalized section of the rural households can avail benefit out of them. Results also showed that local institutions such as local bio-energy markets and barter trade for labor- bioenergy have significant influence on household energy choice. Decentralized energy systems (DES) can create synergies here, where households rich in bio-energy resources (large landlords) can sell their surplus bio-energy to DES, and their money generated can be used to pay cash wage to local agricultural labors (instead of paying them in bio-energy residues). While, this will increase the paying capacity of poor households for energy services, the local sourcing of energy feedstocks will also result in cheap modern energy production benefitting both rich and poor households. Results also indicated that social factors such as higher female education and young age of household head are associated with household's increased modern cooking energy consumption in its total cooking energy mix. Households' education and awareness programs on modern energy utilization can facilitate their modern energy transition.

The thesis utilized linear optimization technique to formulate a village energy model in GAMS (General Algebraic Modeling Software). The model identified an optimal Village Energy System (VES) considering all possible energy sources and technologies (energy systems), their interdependencies as well as their linkages with food security. The results confirmed energy systems interdependencies for rural communities and verified that the cooking, lighting, power and irrigation energy systems of the village community are interlinked and should not be modeled in isolation to each other. For instance, results showed that the levelized cost of electricity generation from biomass gasifier power system is 2.54 INR/ MJ as compared to 2.89 INR/ MJ from grid electricity-battery based power system. However, model selected the latter for fulfilling village's night time power needs while it assigned higher shadow price of 0.143 INR / MJ to the former. This happened because possible utilization of gasifier power system was expected to create scarcities of local bio-energy resources, resulting in costlier cooking energy system for the village. This result has a practical significance as such bio-energy based initiatives may fail on the ground if such energy systems interdependencies are overlooked. The results also showed that DES provides demand side energy management opportunities with different energy prices at different timings of the day. With this, certain energy intensive activities of the communities (such as agro-processing etc.) can be shifted to those times of the day when energy price is cheaper, and this can lead to increased productive activities in the village. Results also indicated that the improved bioenergy cook stoves can bring economic benefits to the rural communities and they also fit with the taste considerations of the households. However, awareness must be spread amongst rural communities on this technology. It was also observed that biogas technology leads to a very optimal VES, where VES entrepreneur benefits from low net energy system costs and sale of biogas slurry, and local communities benefit with reduced energy tariffs and external costs. However, for the successful biogas development, it is important that rural communities must be educated on the benefits of biogas slurry and misconceptions on biogas technology must be eliminated. Results also indicated that the government subsidies on bio-energy technologies such as gasifier or biogas may not be fruitful, as these technologies compete for the bio-energy feedstocks with other energy systems and food security of communities. Due to this, it may happen that local enterprises first avails government subsidies on such bio-energy technologies, but these projects ultimately fail on ground if their interdependencies with other energy systems and food security are overlooked. The results also showed that high costs of finance can hamper the development of decentralized renewable energy systems. In this regard, soft financing on such systems can be very helpful. Business/institutional models with combination of community and entrepreneurial approach can mitigate financing risks perceived by banks towards such energy systems.

Lastly, the thesis analyzed the impacts of village energy system (VES) on the welfare of its rich and poor households. For this, an agricultural household model linked with VES, was implemented on GAMS. Here, household had the opportunity to purchase VES's energy services and sell its bio-energy feedstocks to VES. Results showed that VES's energy services are more attractive for the poor household in comparison to the rich household as the former's budgetary constraint, lower energy demands, and high costs of investment (i.e. discount rate) make its personal energy investments more difficult. As a result, poor household intensified its energy utilization for agriculture. For the poor household, this interaction with VES led to its increased agricultural production with around 22% increase in farm area cultivation in summers, as well as led to reduction in its off-farm labor by around 11% which is then utilized in its own agriculture. Overall, this interaction resulted in around 4% increase in poor household's annual income. On the down side, this interaction led to poor household shifting towards dirtier cooking energy technologies resulting in increased external costs and CO_2 emissions by around 27% and 45%, respectively. On the other hand, VES did not impact rich household's food production and only marginally increased its economic gain. However, it led to rich household shifting towards cleaner cooking energy thereby resulting in reduction of its external costs almost by half. This happened because rich household found it profitable to sell its wood resources to VES and shift to biogas benefitting from its larger cattle endowment and the opportunity of using biogas slurry in its large farm. This result explains that why some decentralized initiatives receive only partial success or benefit only certain category of households. Therefore, energy development strategies should consider such heterogeneities amongst their target households and policies must be accordingly framed. The results also showed that while decentralized energy initiatives can create synergies with certain activities of the household, they may also have tradeoffs with others. For instance, crop residue or wood-based gasifier power system can offer a viable power system to a community but could also create scarcity of bioenergy resources for its cooking energy needs. For the long-term sustainability of decentralized energy initiatives, such tradeoffs should be tackled simultaneously.

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Appendix

Appendix 1: Economic and emission characteristics of different energy technologies

Appendix 1 presents the capital costs, fuel costs, operational costs, efficiencies, life of the capital, system degradation rates, carbon dioxide emissions, carbon monoxide and TSP (total suspended emissions) associated with all the relevant energy technologies, which were discussed in Table 4.1. Utilizing equation 1a of the section 4.3.1 (calculation of levelized cost of energy generation), levelized costs of such energy systems are presented in this section. For the bioenergy-based technologies, LCOE has been presented both considering bio-energy feedstock costs and without bio-energy feedstock costs. It also presents health damage costs and carbon emissions in the production of each MJ of useful energy from the respective energy systems. The costs to health from domestic energy use are based on emissions from carbon monoxide (CO) and particular matter (PM 2.5) of energy sources. The source of these costs is Victoria Transport Policy Institute website (VTPI undated). VTPI undated quotes Litman and Doherty 2009 which utilizes RWDI Inc. 2006 data to present the health damage costs due to the emission pollution of CO and PM 2.5 from the vehicles in Canada. While calculating the health damage by PM2.5 and CO on human health, RWDI Inc. 2006 considers the quantified health effects (in monetary values, i.e., Canadian dollars) of these emissions on premature mortality, chronic bronchitis, asthma symptom days, acute respiratory symptoms, respiratory hospital admissions, cardiac hospital admissions, emergency room visits, restricted activity days and the cognitive effects. It is to be noted that RWDI Inc. 2006 calculated the health damage costs in the settings of Canada. For converting these values for the Indian settings, the ratio of GDP per capita between India and Canada was calculated. Thereafter this ratio was multiplied by the health damage cost of CO and PM2.5 as given in RWDI Inc. 2006.

Table A1.1 below presents the above discussed information for the power systems which have been considered in the research (as discussed in Chapter 4 and 5). Table A1.2, A1.3 and A1.4 gives similar information for cooking, lighting and irrigation energy systems considered in the study.

Table A1.1: Economic and Emission characteristics of different cooking energy technologies

Cost Characteristics	Power Systems considered					
	Solar PV	Battery backup	Diesel	Grid Connection	Gasifier based power	Biogas Power
Investment on Capital	80,000 Rs/ KW (MNRE 2017, Prasanna MG et al. 2015)	65 Rs/ Ah (Quotation by Artheon Pvt. Ltd)	20,000 Rs/ KW (Intelligent Energy Company, 2012 and Field Research)	- Connection fees: Rs 1,500 - Wiring: Rs 2,000 per installation (Field Research)	- Gasifier: Rs 50,000 per KW - Engine and Alternator- Rs 32,000 per KW (Mahapatra S et al. 2009, Interview with TERI experts on bio-energy)	- Digester: Rs 10,000/ m^3 - Engine and Alternator- Rs 32,000 per KW - Scrubber: Rs 4,000/ m^3 biogas plant (Mahapatra S et al. 2009, TERI expert, Field Research)
Life of the capital (years)	15 (Prasanna MG et al. 2015)	5 (Quotation by Artheon Pvt. Ltd)	10 (field Research)	7 (for wiring) (Field Research)	15- gasifier, 10-engine & alternator (Mahapatra S et al. 2009)	15- digester, 10-engine & alternator (Interview with TERI experts)
Fuel Costs/ Solar Insolation	Solar insolation of 5.05 $Kwh/m^2/day$ in Rae Bareilly district of UP (TERI 2013)	0	0.33 liter/ KwH @ Rs 50/liter (Kirloskar company, SSEF undated, Field Research)	0	1.8 kg/ KwH @ Rs 1.5/ kg (Mahapatra S et al. 2009, Interview with TERI experts on bio-energy)	25 kg dung/m^3 of biogas @ Rs 0.5/ kg of dung. Assuming biogas to electricity efficiency of 0.30) (Charles Banks 2009 and Interview with TERI experts)
O&M costs	1 % of the capital cost per year (Mahapatra S et al. 2009)	0 (as quotation is for low maintenance batteries and includes warranty)	2% of the capital cost per year (Field Research)	- Rs 180/ KW/ month (unmetered domestic) - Rs 50/KW/ month + Rs 2.2/kWh (metered domestic) - Rs 450/ KW/ month (unmetered commercial) - Rs 65/KW/ month + Rs 3/kWh (metered commercial) (UPPCL 2015)	- Rs 1.5/ Kwh produced (ibid) - manpower of 8 hours/ day (ibid)	- 1 Rs/ hour of operation (Mahapatra S et al. 2009) - 2 hours/ day of manpower (Field Research)

Cost Characteristics	Power Systems considered					
	Solar PV	Battery backup	Diesel	Grid Connection	Gasifier based power	Biogas Power
System degradation rate	0.5%/ year (Jordan CD and Kurtz SR. 2012)	0; Depth of discharge considered to be 50% (Interview with TERI experts)	0	0	0	0
LCOE (Rs/ Kwh) with bio-energy costs & discount rate of 10%	5.79	7.11	17.19 (assuming 12 hours of operation per day)	- 2.61 (metered domestic) - 3.29 (metered commercial)	9.23 (assuming 12 hours of operation per day)	10.67
LCOE (Rs/ MJ) with bio-energy costs & discount rate of 10%	1.61	1.97	4.77	- 0.72 (metered domestic) - 0.91 (metered commercial)	2.56	2.965
CO emissions (gm/MJ delivered)	0	0	0.81 (Uma et al. 2004)	0	1.38 (Swedish Energy Agency, 2011)	0.21 (Argonne National Laboratory. 2014)
TSP emissions (gm/MJ delivered)	0	0	0.069 (Uma et al. 2004)	0	0.0069 (Swedish Energy Agency, 2011)	0.0098 (Argonne National Laboratory. 2014)
Health damage cost (Rs/MJ delivered)	0	0	0.067 (VTPI undated & Uma et al. 2004) *	0	0.0076 (VTPI undated & Swedish Energy Agency, 2011)	0.0097 (VTPI undated & Argonne National Laboratory. 2014)
CO2 emissions per MJ (kg/MJ delivered)	0	0	0.216 (Sovacool BK 2008)	0	0.08 (TERI's experimental data)	0.054 (Argonne National Laboratory. 2014)

Source: Numerous sources as indicated in the table above

Note: Energy loads of poor households are lower than rich households. Biogas engines are generally available in certain fixed power ratings. When, they are run on partial loads, result in lower efficiency (50% then normal). Accordingly, LCOE of biogas power for poor hh is 2.77 Rs/ Mj

Table A1.2: Economic and Emission characteristics of different cooking energy technologies

Cost Characteristics	**Cooking Energy Systems considered**							
	Traditional-Dung	Improved-Dung	Traditional-wood	Improved-wood	Traditional-Crop Residues	Improved-Crop Residues	Biogas	LPG
Investment on Capital (Rs)	0	2000 (Jade Oudejans 2012 (Chulika cookstove))	0	2000 (Jade Oudejans 2012 (Chulika cookstove))	0	2000 (Jade Oudejans 2012 (Chulika cookstove))	Rs 10,000/ m^3 (Interview with TERI researcher and biogas technicians in field & Mahapatra S et al. 2009)	Connection fees and cook stove 4500 (Field Research)
Life of the capital (years)	N/A	5 (Interview with TERI experts on bio-energy)	N/A	5 (Interview with TERI experts on bio-energy)	N/A	5 (Interview with TERI experts on bio-energy)	Digester- 15, cookstove-5 (Interview with TERI experts on bio-energy)	5 (Interview with TERI experts on bio-energy)
Fuel Costs (Rs/ Kg)	2.5 (Field Research)	2.5 (Field Research)	6 (Field Research)	6 (Field Research)	1.5 (rice residues) (Field Research)	1.5 (rice residues) (Field Research)	Rs 0.5/kg (fresh dung) @ 25kg dung/ m^3 of biogas (Field Research)	Rs 32/ ltr (Field Research)
Energy Density of Fuel (MJ/Kg)	12 (Bhutto et al. 2011)	12 (Bhutto et al. 2011)	19.71 (Nahar 2002)	19.71 (Nahar 2002)	15.26 (Huang et al. 2008)	15.26 (Huang et al. 2008)	22 (biogas, MJ/m3) (Charles Banks 2009)	45.56 (Nahar 2002)
Efficiency of conversion to useful energy	0.094 (USEPA 2000)	0.156 (TERRE 2010) *	0.18 (USEPA 2000)	0.3 (TERRE 2010)	0.098 (USEPA 2000)	0.163 (TERRE 2010)*	0.57 (USEPA 2000)	0.536 (USEPA 2000)
O&M costs per year	0	0	0	0	0	0	1 hour/ day of labor	0
LCOE (Rs/ MJ) considering i/p bioenergy costs	2.21	1.40	1.69	1.03	1.00	0.65	1.90	1.47

Cost Characteristics	Cooking Energy Systems considered							
	Traditional-Dung	Improved-Dung	Traditional-wood	Improved-wood	Traditional-Crop Residues	Improved-Crop Residues	Biogas	LPG
LCOE (Rs/ MJ) without considering i/p bioenergy costs and input labor	0	0.074	0	0.023	0	0.056	0.309	1.50
CO (gm/MJ delivered)	44.85 (USEPA 2000)	4.76 (TERRE 2010)*	24.19 (USEPA 2000)	2.57 (TERRE 2010)	38.14 (USEPA 2000)	4.05(TERRE 2010)*	0.19 (USEPA 2000)	0.60 (USEPA 2000)
TSP (gm/MJ delivered)	1.99 (USEPA 2000)	1.2(TERRE 2010)*	0.37 (USEPA 2000)	0.228 (TERRE 2010)	0.63 (USEPA 2000)	0.38(TERRE 2010)*	0.05 (USEPA 2000)	0.02 (USEPA 2000)
Health damage cost (Rs/MJ delivered)	1.96 VTPI undated & USEPA 2000)	1.17 VTPI undated & TERRE 2010)	0.38 VTPI undated & USEPA 2000)	0.222 VTPI undated & TERRE 2010	0.63 VTPI undated & USEPA 2000)	0.37 VTPI undated & TERRE 2010	0.05 VTPI undated & USEPA 2000)	0.02 VTPI undated & USEPA 2000)
CO2 (Kg/MJ delivered)	1.13 (USEPA 2000)	0.81 (USEPA 2000)	0.54 (USEPA 2000)	0.34 (USEPA 2000)	1.01 (USEPA 2000)	0.80 (USEPA 2000)	0.14 (USEPA 2000)	0.127 (USEPA 2000)

Source: Numerous sources as indicated in the table above

(TERRE 2010)*The literature lacks recent studies on the efficiencies/ emissions of improved cookstove using dung cake and crop residues, and most stress is given on wood. So, following strategy was used to calculate efficiencies of improved dung and crop residues-based cook stoves. First ratio of efficiency/ emissions of traditional firewood cookstove and traditional dung cake stove/ traditional crop residue stove was measured based on USEPA 2000. Then they are multiplied by the efficiency/ emissions of improved firewood cookstove whose efficiency is 0.30 (model chulika with natural draft style (TERRE Policy Center, 2010)) for getting efficiency/ emissions values of improved stove with dung and improved stove with crop residues respectively.

Table A1.3: Economic and Emission characteristics of different lighting systems

Cost Characteristics	**Lighting Systems considered**							
	Kerosene	Solar + LED light	Solar with back up + LED light	Grid electricity + LED light	Grid electricity battery backup + LED light	Diesel Genset + LED light	Biogas based mantle light	Gasifier + LED light
Lumen output	7.8 lumens/ 0.01 liter (Evan Mills 2003)	76 lumen/ Watt (Philips website)					792 lumens/ 0.15 m^3 (SNV 2011, Mahapatra et al. 2009)	76 lumen/ Watt (Philips website)
Lumen hours output	780 lumen hours/ liter	76000 lumen hours/ Kwh	76000 lumen hours/ Kwh	76000 lumen hours/ Kwh	76000 lumen hours/ Kwh	76000 lumen hours/ Kwh	5280 lumen hours/ m^3	76000 lumen hours/ Kwh
Lumen hours output per unit energy (MJ)	20.05	21111.1	21111.1	21111.1	21111.1	21111.1	240	21111.1
LCOE (Rs/ MJ of energy sources) considering i/p bioenergy costs & discount rate of 10%	1.32 *	1.61**	3.62**	- 0.72 (metered domestic) - 0.91 (metered commercial) **	- 2.70 (metered domestic) - 2.89 (metered commercial) **	4.77**	2.96***	2.56**
LCOE (Rs/ million lumen hours (net present cost)) considering i/p bioenergy costs & discount rate of 10%	66318.87	76.31	171.52	- 34.43 (metered domestic) - 43.35 (metered commercial)	- 128.08 (metered domestic) - 137 (metered commercial)	226.21	7954.12	121.49

Cost Characteristics	**Lighting Systems considered**							
	Kerosene	Solar + LED light	Solar with back up + LED light	Grid electricity + LED light	Grid electricity battery backup + LED light	Diesel Genset + LED light	Biogas based mantle light	Gasifier + LED light
CO (gm/ million lumen hours delivered)	40396.15 (USEPA 2000)	0	0	0	0	38.15 (Uma et al. 2004)	799 (SNV 2011, USEPA 2000)	65.78 (Swedish Energy Agency, 2011)
TSP (gm/ million lumen hours delivered)	1147 (USEPA 2000)	0	0	0	0	3.28 (Uma et al. 2004)	215 (SNV 2011, USEPA 2000)	0.32 (Swedish Energy Agency, 2011)
Health damage cost (Rs/ million lumen hours delivered)	1138.54 (USEPA 2000 & VTPI 2017)	0	0	0	0	3.21 (Uma et al. 2004 and VTPI undated)	209.15 (SNV 2011, USEPA 2000, VTPI undated	0.36 (Swedish Energy Agency, 2011 and VTPI undated)
CO_2 (kg/ million lumen hours delivered)	7071 (USEPA 2000)	0	0	0	0	10.23 (Sovacool 2008)	612.67 (USEPA 2000)	3.78 (TERI experimental data)

Source: Numerous sources as indicated in the table above

* LCOE is calculated using the following information: Kerosene energy density: 37.6 MJ/ liter (Evan Mills 2003), efficiency of kerosene: 0.5 (USEPA 2000), Cost of kerosene: Rs 25/ liter (Field Research)

** For LCOE, please see table A1.1

*** For LCOE of biogas, please see table A1.2

Table A1.4: Economic and Emission characteristics of different irrigation technologies

Cost Characteristics	Irrigation Energy Systems considered				
	Solar Water Pump	Grid electricity-based Tube well	Diesel Engine	Biogas based pump	Biomass Gasifier based pump
Investment on Capital (Rs)	- 439,000 (set consisting of 4.5 KW solar, 5 HP motor) - 12-20,000 (Boring) (MNRE 2017, Field Research)	- 70,000 (connection fees, bribe, wiring, poles) - 15-20,000 (Motor, Pulley & boring for 7 HP) (Field Research)	- 35000 (7 HP) - 15-20,000 (Boring & pump for 7 HP) (Field Research)	- Gasifier: Rs 50,000 per KW - Engine and Alternator- Rs 32,000 per KW - Pump &boring: Rs 1,000- 1,750/ HP (Mahapatra S et al. 2009, Interview with TERI experts on bio-energy)	- Digester: Rs 10,000/ m^3 - Engine and Alternator- Rs 32,000 per KW - Scrubber: Rs 4,000/ m^3 biogas plant - Pump &boring: Rs 1,000- 1,750/ HP (Mahapatra S et al. 2009, Interview with local biogas technicians, TERI expert on bio-energy, Field Research)
Life of the capital (years)	15	10- pulley and motor	10- Engine	15- gasifier, 10-engine & alternator (Mahapatra S et al. 2009)	15- digester, 10-engine & alternator (Interview with TERI experts on bio-energy)
Fuel Costs (Rs/ Kg)	0	0	Efficiency- 35% and fuel cost of Rs 50/ liter (SSEF undated and Field Research)	0.45 kg/ MJ @ Rs 1.5/ kg (Mahapatra S et al. 2009, Interview with TERI experts on bio-energy)	25 kg dung/m^3 of biogas @ Rs 0.5/ kg of dung. Assuming biogas to mechanical energy efficiency of 0.35) (Charles Banks 2009 and Interview with TERI experts on bioenergy)
O&M costs per year	1% of capital cost per year (Mahapatra S et al. 2009)	- Unmetered: Rs 100 + Rs 100/ HP - Metered: Rs 30/ HP + Rs 1/ kWh (UPPCL 2015)	5% of capital costs per year (field research)	- Rs 0.38/ MJ produced (ibid) - manpower of 8 hours/ day (ibid)	- 1 Rs/ hour of operation (Mahapatra S et al. 2009) - 2 hours/ day of manpower (Field Research)

Cost Characteristics	Irrigation Energy Systems considered				
	Solar Water Pump	Grid electricity-based Tube well	Diesel Engine	Biogas based pump	Biomass Gasifier based pump
LCOE (Rs/ MJ delivered) considering input bioenergy costs and discount rate of 10%	2.83	0.63	4.58	2.28	2.52
LCOE (Rs/ MJ delivered) without considering input bioenergy costs and discount rate of 14%	3.35	0.70	4.65	N/A as this is not operated at household level so bio-energy is purchased	0.95
CO (gm/MJ delivered)	0	0	0.81 (Uma et al. 2004)	1.38 (Swedish Energy Agency, 2011)	0.21 (Argonne National Laboratory. 2014)
TSP (gm/MJ delivered)	0	0	0.069 (Uma et al. 2004)	0.0069 (Swedish Energy Agency, 2011)	0.0098 (Argonne National Laboratory. 2014)
Health damage cost (Rs/MJ delivered)	0	0	0.098 (VTPI undated)	0.0076 (VTPI undated & Swedish Energy Agency, 2011)	0.0097 (VTPI undated & Argonne National Laboratory. 2014)
CO2 (Kg/MJ delivered)	0	0	0.216 (Sovacool 2008)	0.08 (TERI's experimental data)	0.054 (Argonne National Laboratory. 2014)

Source: Numerous sources as indicated in the table above

Note 1: External costs and CO2 emissions of Biomass gasifier-based pump and Biogas based pump is considered same Biomass gasifier based power and Biogas based power respectively

Note 2: Irrigation energy requirements of poor households is 25% than that of rich households. Accordingly, in the modelling, tubewell utilization for poor household is assumed to be 25% compared to rich households and therefore LCOE of grid electricity based tubewells for poor household is Rs 3.23 per MJ.

Appendix 2: Summary of energy situation in different surveyed villages of UP

Table A2.1 summarize the energy situation in each of the surveyed villages in Uttar Pradesh. Here, row a to row k presents the general characteristics of each of the surveyed village. Row i to row r presents the energy situation in each of the surveyed village. Row m to row af presents the prices of energy commodities in the local markets in each surveyed village.

Table A2.1: Summary of energy situation in each of the surveyed village in UP

S.N	Village Characteristics	MG	OK	MP	BM	MH	AY	MM	NV
a	Distance from District Head Quarter (kms)	8	3	11	9	18	13	22	14
b	Distance from nearest market (kms)	7	3	11	9	1	5	10	3
c	Average HH farm size (acres)	1.42	0.7	1.57	2.47	6.23	1.47	2.19	1.51
d	Livestock per HH (excl. calves) [Nos]	0.79	0.82	1.45	1.87	2.9	1.7	1.9	1.5
e	Private trees per HH (nos)	3.63	0.71	26.25	56.1	3.2	5.2	4.5	35.73
f	Non-agricultural male labor days per HH per year*	265.2	364.7	243	341	133.83	137.8	236.2	280.7
g	Non-agricultural male labor days per HH per year* (Regular Job)	170	155.2	128	273.2	111.7	127.4	227.9	236.5
h	Caste of village chief (Upper caste =1, Lower Caster=0)	1	0	0	0	1	0	1	0
i	Distance from Gas agency (kms)	1	3	10	6	1	8	10	4
j	% of HHs under poverty line(BPL)	61.0	21.6	77.5	57.1	8.3	34.5	41.5	17.5
k	Proximity to government or community forests/ wastelands	No	No	No	Yes	No	No	Yes	No
l	Percentage of HHs with LPG connections in village	50%	37%	20%	37%	83%	55%	53%	42%
m	% of HHs with primary LPG	32%	31%	10%	17%	67%	19%	10%	5%
n	HHs with legal electricity	61.0 %	66.7 %	35.0 %	45.7 %	100.0 %	63.8 %	17.1 %	37.5 %
o	HHs with illegal electricity	8.5%	13.7 %	40.0 %	11.4 %	0.0%	20.7 %	70.7 %	2.5%
p	HHs with personal big solar system	10.2 %	3.9%	0.0%	7.1%	0.0%	3.4%	0.0%	5.0%

S.N	Village Characteristics	MG	OK	MP	BM	MH	AY	MM	NV
q	HHs with battery storage	16.9 %	7.8%	0.0%	2.9%	75.0%	10.3 %	9.8%	30.0 %
r	HHs with rechargeable Electric lamps (Chinese light)	22%	13.7 %	2.5%	8.6%	0%	17.2 %	36.6 %	5%
s	Price of cattle dung cake in local market (Rs/kg)	8	8	6	5	-	2.5	2.5	2.5
t	Firewood price (Rs/ kg)	7	7	5-6	5-6	7	7	0	7
u	Rate (kg of sugarcane dry leaves/hr of labor)	4-6	4-6	NA	NA	0	NA	NA	4-6
v	Rate (kg of mustard or pigeon pea straw/hr of labor)	4-5	4-5		4-5	4-5			4-5
w	Rate of Rice Husk	Barter trade (explained in the text below), however in monetary terms it is around Rs 2 to 2.5 per kg.							
x	Rate of rice straw (Rs/ kg)	Rs 100 till Rs 150/ Quintal depending on the peak or off-peak season							
y	Rate of wheat straw (Rs/ kg)	Rs 400 till Rs 550/ Quintal depending on the peak or off-peak season							
z	Rate of water sale with diesel pumps (Rs/ Hour)	150	150	150	150	150	120	0	150
aa	Rate of water sale with electric pumps (Rs/ Hour)	100	100	60	100	90	80	30	100
ab	PDS Kerosene price (Rs/ l)	19	19	17	17	17	17	17	17
ac	Open market Kerosene price (Rs/ l)	40	40	35	35	35	30	35	40
ad	PDS LPG price (Rs/ltr)	33	33	33	33	33	33	33	33
ae	Open market LPG price (Rs/ l)	80	80	80	80	80	100	100	100
af	Diesel price (May 2015)	50	50	50	50	50	50	50	50
Source: Author’s own field surveys									

Appendix 3: GAMS Model: Village Energy System

This appendix presents the GAMS model that has been written to formulate an optimal village energy system, considering energy system interdependencies and linkages with food security. While considering these interdependencies, the objective of the model is to minimize total net annual costs for energy generation (discounted annual net present value considering 15-year horizon) for meeting village's annual cooking, lighting, power and irrigation energy needs. To implement different scenarios in the model, following has been done:

- The model presented in this appendix is for scenario 1 (Business-as-usual scenario)
- To implement scenario 2 (health damage costs), health damage costs associated with technologies (health costs per unit generation) are added in the objective function.
- To implement Scenario 3 (sale value of biogas slurry), biogas slurry is assigned the value of Rs 0.5/ kg which is otherwise 0 in Scenario 1 and Scenario 2.
- To implement scenarios considering removal of grid subsidies (Scenario 4), subsidies on renewable energy technologies (Scenario 5), high discount rates associated with energy technologies (Scenario 6), the energy systems costs (levelized costs) are changed accordingly in the model

**** Following is the declaration and definition of variables used in the model***

free variable v_obj annual costs for energy and lighting generation (discounted annual net present value considering 15-year time horizon)
;

positive variable
t_dung useful energy taken from dung cake burnt in traditional cookstove in a year (MJ per year)
i_dung useful energy taken from dung cake burnt in improved cookstove in a year (MJ per year)
t_wood useful energy taken from wood burnt in traditional cookstove in a year (MJ per year)
i_wood useful energy taken from wood burnt in improved cookstove in a year (MJ per year)
t_crop useful energy taken from crop residues burnt in traditional cookstove in a year (MJ per year)
i_crop useful energy taken from crop residues burnt in improved cookstove in a year (MJ per year)
lpg useful energy taken from LPG burnt in LPG cook stove in a year (MJ per year)
bgas_cook useful energy taken from biogas burnt in biogas stove in a year (MJ per year)
slurry_prod annual amount of slurry produced from different biogas based technologies in energy system (kgs per year)
n_ker_light million lumen hours per year received from kerosene lamp lighting in night time (m lumenhours per year)
n_solbat_light million lumen hours per year received from solar (with battery) based LED lighting in night time (m lumenhours per year)
n_grid_light million lumen hours per year received from grid electricity based incandescent bulb lighting in night time (m lumenhours per year)

n_gridbat_light million lumen hours per year received from grid plus battery based incandescent bulb lighting in night time (m lumenhours per year)
n_disgen_light million lumen hours per year received from diesel electricity based LED lighting in night time (m lumenhours per year)
n_gasifier_light million lumen hours per year received from gasifier electricity based LED lighting in night time (m lumenhours per year)
n_biogas_light million lumen hours per year received from biogas mantle lighting in night time (m lumenhours per year)
n_lpg_light million lumen hours per year received from LPG mantle lighting in night time (m lumenhours per year)
d_ker_light million lumen hours per year received from kerosene lamp lighting in day time (m lumenhours per year)
d_solbat_light million lumen hours per year received from solar (with battery) based LED lighting in day time (m lumenhours per year)
d_grid_light million lumen hours per year received from grid electricity based incandescent bulb lighting in day time (m lumenhours per year)
d_gridbat_light million lumen hours per year received from grid plus battery based incandescent bulb in day time (m lumenhours per year)
d_disgen_light million lumen hours per year received from diesel electricity based LED lighting in day time (m lumenhours per year)
d_gasifier_light million lumen hours per year received from gasifier electricity based LED lighting in day time (m lumenhours per year)
d_biogas_light million lumen hours per year received from biogas mantle lighting in day time (m lumenhours per year)
d_sol_light million lumen hours per year received from solar without battery based LED lighting in day time (m lumenhours per year)
d_lpg_light million lumen hours per year received from LPG mantle lighting in day time (m lumenhours per year)
n_solbat_power million lumen hours per year received from solar plus battery based lighting in day time (m lumenhours per year)
n_grid_power useful electricity taken from solar plus battery for non lighting electrcity in night time(MJ per year)
n_gridbat_power useful electricity taken from grid plus battery for non lighting electrcity in night time(MJ per year)
n_disgen_power useful electricity taken from diesel generator for non lighting electrcity in night time(MJ per year)
n_bgas_power useful electricity taken from biogas power for non lighting electrcity in night time(MJ per year)
n_gasifier_power useful electricity taken from gasifier for non lighting electrcity in night time(MJ per year)
d_sol_power useful electricity taken from solar without battery for non lighting electrcity in day time(MJ per year)
d_solbat_power useful electricity taken from solar with battery for non lighting electrcity in day time(MJ per year)

d_grid_power useful electricity taken from grid for non lighting electrcity in day time(MJ per year)
d_gridbat_power useful electricity taken from grid plus battery for non lighting electrcity in day time(MJ per year)
d_disgen_power useful electricity taken from diesel generator for non lighting electrcity in day time(MJ per year)
d_bgas_power useful electricity taken from biogas for non lighting electrcity in day time(MJ per year)
d_gasifier_power useful electricity taken from gasifier for non lighting electrcity in day time(MJ per year)
swp_irrig useful energy taken from solar water pump for irrigation (MJ per year)
bgas_irrig useful energy taken from biogas based water pump for irrigation (MJ per year)
dis_irrig useful energy taken from diesel engine based water pump for irrigation (MJ per year)
grid_irrig useful energy taken from grid electricity based water pump or tubewell for irrigation (MJ per year)
gasifier_irrig useful energy taken from gasifier based pump for irrigation (MJ per year)
ann_manure_noncrop annual amount (kg) of manure used for non crops such as energy (kgs per year)
cook_energy_price average price of cooking from the usage of different cooking energy types (Rs per MJ)
tot_healthcost total health damage costs per year from energy system in Rs because of CO and PM emissions of the combined energy system of cooking lighting powr and irrigation (Rs per year)
tot_co2emis tonnes of CO2 emission per year associated with the energy system of cooking lighting powr and irrigation (tonnes per year)
hh_revenue total household revenues generated from the sale of bioenergy resources to village energy system (Rs per year)
day_power_price average price of power in day time from the usage of different power types (Rs per MJ)
night_power_price average price of power in night time from the usage of different power types (Rs per MJ)
day_light_price average price of light in day time from the usage of different lighting types (Rs per million lumen hours)
night_light_price average price of light in night time from the usage of different lighting types (Rs per million lumen hours)
irrig_ener_price average price of irrigation from the usage of different irrigation types (Rs per MJ)
ann_manure_crop annual amount of manure used for crops by households in village including the amount of slurry generated by energy system (kg per year)
perc_enerman_totman ratio of total manure used for energy in kg divided by total manure available in village in kgs (%)
perc_enercrop_totcrop ratio of total crop residues used for energy in kg divided by total crop residues available in village in kgs (%)
perc_enerwood_totwood ratio of total wood used for energy in kg divided by total wood available in village in kgs (%)
;

**** The following inputs data (on technologies, on village energy demands and bio-energy constraints) in the model***

Parameters p_rawdung   price of raw dung (Rs per kg)
;
p_rawdung=0.5
;
Parameters p_rawwood   price of raw wood (Rs per kg)
;
p_rawwood = 6
;
Parameters p_rawcropresidues   price of raw crop residues (Rs per kg)
;
p_rawcropresidues = 1.5
;
Parameters p_tdung   levelized cost of useful enrgy from dung cake in traditional stove (Rs per MJ)
;
p_tdung=2.21
;
Parameters p_idung   levelized cost of useful enrgy from dung cake in improved stove (Rs per MJ)
;
p_idung=1.40
;
Parameters p_twood   levelized cost of useful enrgy from wood in traditional stove (Rs per MJ
1.409)
;
p_twood=1.69
;
Parameters p_iwood   levelized cost of useful enrgy from wood in improved stove (Rs per MJ)
;
p_iwood=1.03
;
Parameters p_tcrop levelized cost of useful enrgy from crop residue in traditional stove (Rs per MJ)
;
p_tcrop=1.00
;
Parameters p_icrop levelized cost of useful enrgy from cop residue in improved stove (Rs per MJ)
;
p_icrop=0.65
;
Parameters p_lpg   levelized cost of useful enrgy from LPG (Rs per MJ1.43)
;
p_lpg=1.47
;
Parameters p_bgascook levelized cost of useful enrgy from biogas cooking (Rs per MJ)
;
p_bgascook= 1.9
;
Parameters tot_cookdem total cooking energy demand (MJ per year)
;
tot_cookdem= 2798867.44

;
Parameters ann_manure_tot total cattle manure produced per year which is used for energy and manure purposes(kg per year)
;
ann_manure_tot= 3922497.408
;
Parameters tot_ann_forest total forest residue produced per year(kg per year)
;
tot_ann_forest= 332466.6
;
Parameters tot_ann_cropres_nonliv   total crop residue produced per year(kg per year) which are not for livestock this includes sugarcane dry leaves rice husk and 32% of rice straw
;
tot_ann_cropres_nonliv = 389012.08
;

Parameters tot_ann_LPGsupply total possible LPG supply per year from government under PDS scheme(MJ per year)
;
tot_ann_LPGsupply= 2908550.4
;
Parameters slurry_bgas_ratio amount of slurry manure produced per MJ of useful energy by biogas(kg per MJ)
;
slurry_bgas_ratio= 1.97
;
Parameters slurry_saleprice sale price of slurry(Rs per kg)
;
slurry_saleprice= 0
;
Parameters p_ker_n price of kerosene_light_night (Rs per million lumenhours)
;
p_ker_n= 66318.88
;
Parameters p_sollight   price of solar LED light with battery at night (Rs per million lumenhours)
;
p_sollight= 76.31
;
Parameters p_n_solbatlight   price of solar LED light with battery at night (Rs per million lumenhours)
;
p_n_solbatlight= 171.52
;
Parameters p_n_gridlight price of grid with LED light at night   (Rs per million lumenhours)
;
p_n_gridlight= 43.35
;
Parameters p_n_gridbatlight price of grid with battery with LED light at night   (Rs per million lumenhours)
;
p_n_gridbatlight= 137.00

;
Parameters p_n_disgenlight price of diesel genset with LED light at night (Rs per million lumenhours)
;
p_n_disgenlight= 226.21
;
Parameters p_n_gasifierlight price of biomass gasifier with LED light at night (121.49Rs per million lumenhours)
;
p_n_gasifierlight= 110.45
;
Parameters p_n_biogaslight price of biogas based light mantle (7954.51Rs per million lumenhours)
;
p_n_biogaslight= 7954.51
;
Parameters p_n_lpglight price of LPG based light mantle (Rs per million lumenhours)
;
p_n_lpglight= 7078.78
;
Parameters grid_light_current_sup_night current available grid supply based light at night (million lumenhours per year)
;
grid_light_current_sup_night= 1078.30
;
Parameters grid_light_current_sup_day current available grid supply based light at day (million lumenhours per year)
;
grid_light_current_sup_day= 77.6
;
Parameters tot_light_req_night total lighting requirement at night (million lumenhours per year)
;
tot_light_req_night= 3083.5
;
Parameters tot_light_req_day total lighting requirement at day (million lumenhours per year)
;
tot_light_req_day= 155.23
;
Parameters tot_pos_gridpower_day total possible grid power (non lighting)in day (MJ per year)
;
tot_pos_gridpower_day= 423049.39
;
Parameters tot_pos_gridpower_night total possible grid power (non lighting)in night (MJ per year)
;
tot_pos_gridpower_night= 291292.2
;
Parameters tot_power_req_day total power (non lighting) requirement at day (MJ per year)
;
tot_power_req_day= 748542.44
;
Parameters tot_power_req_night otal power (non lighting) requirement at day (MJ per year)
;

tot_power_req_night= 491870.88
;
Parameters tot_irrig_energ_req total irrigation energy requirement (MJ per year)
;
tot_irrig_energ_req= 362913.23
;
Parameters p_sol_power price of solar power (Rs per MJ)
;
p_sol_power= 1.61
;
Parameters p_solbat_power price of solar with battery power (Rs pr MJ)
;
p_solbat_power= 3.62
;
Parameters p_gridpower price of grid power (Rs per MJ)
;
p_gridpower= 0.91
;
Parameters p_gridbat_power price of grid with battery power (Rs per MJ)
;
p_gridbat_power= 2.89
;
Parameters p_disgen_power price of diesel genset power (Rs per MJ)
;
p_disgen_power= 4.77
;
Parameters p_bgas_power price of biogas based power (Rs per MJ)
;
p_bgas_power= 2.96
;
Parameters p_gasifier_power price of gasifier based power (Rs per MJ)
;
p_gasifier_power= 2.56
;
Parameters p_swp_irrig price of solar water pump based irrigation (Rs per MJ)
;
p_swp_irrig= 2.7
;
Parameters p_dis_irrig price of diesel engine based irrigation (Rs per MJ)
;
p_dis_irrig= 4.58
;
Parameters p_grid_irrig price of grid power based irrigation (Rs per MJ)
;
p_grid_irrig= 0.63
;

Parameters p_bgas_irrig price of biogas based irrigation energy (Rs per MJ)
;
p_bgas_irrig= 2.52
;

Parameters p_bgasifier_irrig price of biomass gasifier based irrigation energy (Rs per MJ)
;
p_bgasifier_irrig= 2.28
;
Parameters hdamage_tdung health damage cost per useful energy from traditional dung (Rs per MJ)
;
hdamage_tdung= 1.96
;
Parameters hdamage_idung health damage cost per useful energy from improved dung (Rs per MJ)
;
hdamage_idung= 1.17
;
Parameters hdamage_twood health damage cost per useful energy from traditional wood (Rs per MJ)
;
hdamage_twood= 0.38
;
Parameters hdamage_iwood health damage cost per useful energy from improved wood (Rs per MJ)
;
hdamage_iwood= 0.22
;
Parameters hdamage_tcrop health damage cost per useful energy from traditional crop res (Rs per MJ)
;
hdamage_tcrop= 0.64
;
Parameters hdamage_icrop health damage cost per useful energy from improved crop res (Rs per MJ)
;
hdamage_icrop= 0.37
;
Parameters hdamage_lpg health damage cost per useful energy from lpg (Rs per MJ)
;
hdamage_lpg= 0.020
;
Parameters hdamage_bgas health damage cost per useful energy from biogas (Rs per MJ)
;
hdamage_bgas= 0.05
;
Parameters hdamage_ker health damage cost from kerosene light (Rs per million lumenhours)
;
hdamage_ker= 1138.54
;
Parameters hdamage_sollight health damage cost from solar LED based lighting (Rs per million lumenhours)
;
hdamage_sollight= 0
;

Parameters hdamage_solbatlight health damage cost from lighting based on solar battery with LED (Rs per million lumenhours)
;
hdamage_solbatlight= 0
;
Parameters hdamage_gridlight health damage cost from grid based incandescent lighting (Rs per million lumenhours)
;
hdamage_gridlight= 0
;
Parameters hdamage_gridbatlight health damage cost from lighting based on grid with battery (Rs per million lumenhours)
;
hdamage_gridbatlight= 0
;
Parameters hdamage_disgenlight health damage cost from diesel genset based lighting (Rs per million lumenhours)
;
hdamage_disgenlight= 3.21
;
Parameters hdamage_bgaslight health damage cost from biogas mantle based lighting (Rs per million lumenhours)
;
hdamage_bgaslight= 209.15
;
Parameters hdamage_gasifierpowerlight health damage cost from gasifier based LED lighting (Rs per million lumenhours)
;
hdamage_gasifierpowerlight= 0.36
;
Parameters hdamage_LPGlight health damage cost from LPG mantle lighting (Rs per million lumenhours)
;
hdamage_LPGlight= 99.06
;
Parameters hdamage_sol health damage cost per useful energy from solar power without battery (Rs per MJ)
;
hdamage_sol= 0
;
Parameters hdamage_solbat health damage cost per useful energy from solar power with battery (Rs per MJ)
;
hdamage_solbat= 0
;
Parameters hdamage_grid health damage cost per useful energy from grid power (Rs per MJ)
;
hdamage_grid= 0
;
Parameters hdamage_gridbat health damage cost per useful energy from grid power with battery (Rs per MJ)

;
hdamage_gridbat= 0
;
Parameters hdamage_disgen health damage cost per useful energy from diesel genset (Rs per MJ)
;
hdamage_disgen= 0.067
;
Parameters hdamage_bgaspower health damage cost per useful energy from biogas based power (Rs per MJ)
;
hdamage_bgaspower= 0.0097
;
Parameters hdamage_gasifierpower health damage cost per useful energy from gasifier power (Rs per MJ)
;
hdamage_gasifierpower= 0.0076
;

**** The following are the declarations of the equations for the model***

Equations
con_dung,
con_slurry,
con_dungforcrop,
con_manure,
con_wood,
con_cropres,
con_totcookdem,
con_grid_light_night,
con_grid_light_day,
con_tot_nightlight,
con_tot_daylight,
con_grid_power_day,
con_grid_power_night,
con_tot_daypower,
con_tot_nightpower,
con_tot_irrigation_energydemand,
con_cook_ener_price,
con_healthcost,
con_hhrevenue,
obj,
obj_health,
con_cookenergy_price,
con_daypower_price,
con_nightpower_price,
con_daylight_price,
con_nightlight_price,

con_irrig_ener_price,
con_co2emis,
con_annperc_enerman_totman,
con_annperc_enercrop_totcrop,
con_annperc_enerwood_totwood;

Equations for Cattle dung balance for creating interdependencies between different dung based energy technologies

con_dung.. (t_dung*3/0.094)/12 + (i_dung*3/0.156)/12 + (bgas_cook*25/0.574)/22 + ((((n_biogas_light * 1000000)/240)/0.574)/22)*25 + ((((d_biogas_light * 1000000)/240)/0.574)/22)*25 +(n_bgas_power*25/0.3)/22 + (d_bgas_power*25/0.3)/22 + (bgas_irrig*25/0.35)/22 =L= ann_manure_noncrop ;

Equations for Cattle dung balance that limits dung utilization for energy use and farm fertilizer use

con_slurry.. slurry_prod =E= bgas_cook*slurry_bgas_ratio + n_bgas_power*slurry_bgas_ratio + d_bgas_power*slurry_bgas_ratio + bgas_irrig*slurry_bgas_ratio + ((n_biogas_light * 1000000)/240)*slurry_bgas_ratio + ((d_biogas_light * 1000000)/240)*slurry_bgas_ratio;

con_dungforcrop.. ann_manure_tot =E= ann_manure_noncrop + ann_manure_crop;

con_manure.. ann_manure_crop + slurry_prod =G= 2167125.41;

**** Equations for Wood balance for creating interdependencies between different wood energy technologies***

con_wood.. (t_wood/0.18)/19.71 + (i_wood/0.3)/19.71 =L= tot_ann_forest ;

**** Equations for Crop residue balance for creating interdependencies between different crop residue based energy technologies***

con_cropres.. (t_crop/0.098)/15.26 + (i_crop/0.163)/15.26 + (((n_gasifier_light*1000000)/21111)/3.6)*1.8 + (n_gasifier_power/3.6)*1.8 + (d_gasifier_power/3.6)*1.8 + ((gasifier_irrig/0.9) /3.6)*1.8 =L= tot_ann_cropres_nonliv ;

**** Equations for Energy System Balances dividing energy systems for different times of the day for light and power***

con_totcookdem.. t_dung + i_dung+ t_wood + i_wood+ t_crop+ i_crop+ lpg + bgas_cook =E= tot_cookdem;
con_grid_light_night.. n_grid_light =L= grid_light_current_sup_night ;
con_grid_light_day.. d_grid_light =L= grid_light_current_sup_day ;

con_tot_nightlight.. n_ker_light + n_solbat_light + n_grid_light + n_gridbat_light + n_disgen_light + n_gasifier_light + n_biogas_light =E= tot_light_req_night ;
con_tot_daylight.. d_ker_light + d_sol_light + d_grid_light + d_gridbat_light + d_disgen_light + d_gasifier_light + d_biogas_light =E= tot_light_req_day ;
con_grid_power_day.. d_grid_power =L= tot_pos_gridpower_day ;
con_grid_power_night.. n_grid_power =L= tot_pos_gridpower_night ;
con_tot_daypower.. d_sol_power + d_solbat_power + d_grid_power + d_gridbat_power + d_disgen_power + d_bgas_power + d_gasifier_power =E= tot_power_req_day ;
con_tot_nightpower.. n_solbat_power + n_grid_power + n_gridbat_power + n_disgen_power + n_bgas_power + n_gasifier_power =E= tot_power_req_night;
con_tot_irrigation_energydemand.. swp_irrig + dis_irrig + grid_irrig + bgas_irrig + gasifier_irrig =E= tot_irrig_energ_req;

**** Annual Health Damage Costs from the energy system***

con_healthcost.. t_dung*hdamage_tdung + i_dung*hdamage_idung + t_wood*hdamage_twood + i_wood*hdamage_iwood + t_crop*hdamage_tcrop + i_crop*hdamage_icrop + lpg*hdamage_lpg + bgas_cook*hdamage_bgas
+ n_ker_light*hdamage_ker + n_solbat_light*hdamage_solbatlight + n_grid_light*hdamage_gridlight + n_gridbat_light*hdamage_gridbatlight + n_disgen_light*hdamage_disgenlight+ n_gasifier_light*hdamage_gasifierpowerlight + n_biogas_light *hdamage_bgaslight + n_lpg_light * hdamage_LPGlight
+ d_ker_light*hdamage_ker + d_sol_light*hdamage_sollight + d_grid_light*hdamage_gridlight + d_gridbat_light*hdamage_gridbatlight + d_disgen_light*hdamage_disgenlight+ d_gasifier_light*hdamage_gasifierpowerlight + d_biogas_light *hdamage_bgaslight + d_lpg_light * hdamage_LPGlight
+ d_sol_power*hdamage_sol + d_solbat_power*hdamage_sol + d_grid_power*hdamage_grid + d_gridbat_power*hdamage_grid + d_disgen_power*hdamage_disgen + d_gasifier_power*hdamage_gasifierpower + d_bgas_power*hdamage_bgaspower
+ n_solbat_power*hdamage_solbat + n_grid_power*hdamage_grid + n_gridbat_power*hdamage_gridbat + n_disgen_power*hdamage_disgen + n_bgas_power*hdamage_bgaspower + n_gasifier_power*hdamage_gasifierpower
+ swp_irrig*hdamage_sol + dis_irrig*hdamage_disgen + grid_irrig*hdamage_grid + bgas_irrig*hdamage_bgaspower + gasifier_irrig * hdamage_gasifierpower =E= tot_healthcost;

**** Objective function- minimize total net annual costs for energy generation (discounted net present values considering 15 year time horizon)***

obj.. t_dung*p_tdung + i_dung*p_idung + t_wood*p_twood + i_wood*p_iwood + t_crop*p_tcrop + i_crop*p_icrop + lpg*p_lpg + bgas_cook*p_bgascook
+ d_ker_light*p_ker_n + d_solbat_light*p_n_solbatlight + p_sollight*d_sol_light + d_grid_light*p_n_gridlight + d_gridbat_light*p_n_gridbatlight + d_disgen_light*p_n_disgenlight + d_gasifier_light*p_n_gasifierlight + d_biogas_light*p_n_biogaslight + d_lpg_light * p_n_lpglight

+ n_ker_light*p_ker_n + n_solbat_light*p_n_solbatlight + n_grid_light*p_n_gridlight +
n_gridbat_light*p_n_gridbatlight + n_disgen_light*p_n_disgenlight +
n_gasifier_light*p_n_gasifierlight + n_biogas_light*p_n_biogaslight + n_lpg_light * p_n_lpglight
+ d_sol_power*p_sol_power + d_solbat_power*p_solbat_power + d_grid_power*p_gridpower +
d_gridbat_power*p_gridbat_power + d_disgen_power*p_disgen_power +
d_bgas_power*p_bgas_power + n_gasifier_power*p_gasifier_power
+ n_solbat_power*p_solbat_power + n_grid_power*p_gridpower +
n_gridbat_power*p_gridbat_power + n_disgen_power*p_disgen_power +
d_gasifier_power*p_gasifier_power + n_bgas_power*p_bgas_power
+ swp_irrig*p_swp_irrig + dis_irrig*p_dis_irrig + grid_irrig*p_grid_irrig + bgas_irrig*p_bgas_irrig +
gasifier_irrig * p_bgasifier_irrig - slurry_prod * slurry_saleprice =E= v_obj;

**** Objective function- minimize total net annual costs for energy generation including health costs (discounted net present values considering 15 year time horizon)***

obj_health.. t_dung*p_tdung + i_dung*p_idung + t_wood*p_twood + i_wood*p_iwood +
t_crop*p_tcrop + i_crop*p_icrop + lpg*p_lpg + bgas_cook*p_bgascook
+ d_ker_light*p_ker_n + d_solbat_light*p_n_solbatlight + p_sollight*d_sol_light +
d_grid_light*p_n_gridlight + d_gridbat_light*p_n_gridbatlight + d_disgen_light*p_n_disgenlight +
d_gasifier_light*p_n_gasifierlight + d_biogas_light*p_n_biogaslight + d_lpg_light * p_n_lpglight
+ n_ker_light*p_ker_n + n_solbat_light*p_n_solbatlight + n_grid_light*p_n_gridlight +
n_gridbat_light*p_n_gridbatlight + n_disgen_light*p_n_disgenlight +
n_gasifier_light*p_n_gasifierlight + n_biogas_light*p_n_biogaslight + n_lpg_light * p_n_lpglight
+ d_sol_power*p_sol_power + d_solbat_power*p_solbat_power + d_grid_power*p_gridpower +
d_gridbat_power*p_gridbat_power + d_disgen_power*p_disgen_power +
d_bgas_power*p_bgas_power + d_gasifier_power*p_gasifier_power
+ n_solbat_power*p_solbat_power + n_grid_power*p_gridpower +
n_gridbat_power*p_gridbat_power + n_disgen_power*p_disgen_power +
n_bgas_power*p_bgas_power + n_gasifier_power*p_gasifier_power
+ swp_irrig*p_swp_irrig + dis_irrig*p_dis_irrig + grid_irrig*p_grid_irrig + bgas_irrig*p_bgas_irrig +
gasifier_irrig * p_bgasifier_irrig - slurry_prod * slurry_saleprice + tot_healthcost =E= v_obj;

**** Annual Carbon dioxide emissions from the energy system***

con_co2emis.. (t_dung*1.13 + i_dung*0.81 + t_wood*0.54 + i_wood*0.34 + t_crop*1.01 +
i_crop*0.80 + lpg*0.12 + bgas_cook*0.14
+ n_ker_light*7071.32 + n_solbat_light*0 + n_grid_light*0 + n_gridbat_light*0 +
n_disgen_light*10.23 + n_gasifier_light*3.78 + n_biogas_light *612.67 + n_lpg_light * 610.77
+ d_ker_light*7071.32 + d_sol_light*0 + d_grid_light*0 + d_gridbat_light*0 + d_disgen_light*10.23 +
d_gasifier_light*3.78 + d_biogas_light *612.67 + d_lpg_light * 610.77
+ d_sol_power*0 + d_solbat_power*0 + d_grid_power*0 + d_gridbat_power*0 +
d_disgen_power*0.21 + d_gasifier_power*0.08 + d_bgas_power*0.016
+ n_solbat_power*0 + n_grid_power*0 + n_gridbat_power*0 + n_disgen_power*0.21 +
n_gasifier_power*0.08 + n_bgas_power*0.016

+ swp_irrig*0 + dis_irrig*0.21 + grid_irrig*0 + gasifier_irrig * 0.08)/1000 =E= tot_co2emis;

**** Average prices for energy systems (cooking, lighting in night and day, power in night and day, and irrigation)***

con_cookenergy_price.. cook_energy_price =E= (t_dung*p_tdung + i_dung*p_idung + t_wood*p_twood + i_wood*p_iwood + t_crop*p_tcrop + i_crop*p_icrop + lpg*p_lpg + bgas_cook*p_bgascook)/ tot_cookdem ;

con_daypower_price.. day_power_price =E= (d_sol_power*p_sol_power + d_solbat_power*p_solbat_power + d_grid_power*p_gridpower + d_gridbat_power*p_gridbat_power + d_disgen_power*p_disgen_power + d_bgas_power*p_bgas_power + d_gasifier_power*p_gasifier_power)/ tot_power_req_day ;

con_nightpower_price.. night_power_price =E= (n_solbat_power*p_solbat_power + n_grid_power*p_gridpower + n_gridbat_power*p_gridbat_power + n_disgen_power*p_disgen_power + n_bgas_power*p_bgas_power + n_gasifier_power*p_gasifier_power)/ tot_power_req_night ;

con_daylight_price.. day_light_price =E= (d_ker_light*p_ker_n + d_solbat_light*p_n_solbatlight + d_sol_light * p_sollight + d_grid_light*p_n_gridlight + d_gridbat_light*p_n_gridbatlight + d_disgen_light*p_n_disgenlight + d_gasifier_light*p_n_gasifierlight + d_biogas_light*p_n_biogaslight)/ tot_light_req_day;

con_nightlight_price.. night_light_price =E= (n_ker_light*p_ker_n + n_solbat_light*p_n_solbatlight + n_grid_light*p_n_gridlight + n_gridbat_light*p_n_gridbatlight + n_disgen_light*p_n_disgenlight + n_gasifier_light*p_n_gasifierlight + n_biogas_light*p_n_biogaslight)/ tot_light_req_night;

con_irrig_ener_price.. irrig_ener_price =E= (swp_irrig*p_swp_irrig + dis_irrig*p_dis_irrig + grid_irrig*p_grid_irrig + bgas_irrig*p_bgas_irrig + gasifier_irrig * p_bgasifier_irrig)/ tot_irrig_energ_req;

**** Annual Household revenues from sale of bioenergy to VES***

con_hhrevenue.. hh_revenue =E= ((t_dung*3/0.094)/12 + (i_dung*3/0.156)/12 + (bgas_cook*25/0.574)/22 + (n_bgas_power*25/0.574)/22 + (d_bgas_power*25/0.574)/22 + ((((n_biogas_light * 1000000)/240)/0.574)/22)*25)* p_rawdung + ((t_wood/0.18)/19.71 + (i_wood/0.3)/19.71)*p_rawwood + ((t_crop/0.098)/15.26 + (i_crop/0.163)/15.26 + (((n_gasifier_light*1000000)/21111)/3.6)*1.8 + (n_gasifier_power/3.6)*1.8 + (d_gasifier_power/3.6)*1.8 + ((gasifier_irrig/0.9) /3.6)*1.8)* p_rawcropresidues;

**** Amount of bioenergy feedstock used for energy production to the total bioenergy feedstock available for energy production***

con_annperc_enerman_totman.. perc_enerman_totman =E= ((t_dung*3/0.094)/12 + (i_dung*3/0.156)/12 + (bgas_cook*25/0.574)/22 + ((((n_biogas_light * 1000000)/240)/0.574)/22)*25 + ((((d_biogas_light * 1000000)/240)/0.574)/22)*25 +(n_bgas_power*25/0.3)/22 + (d_bgas_power*25/0.3)/22 + (bgas_irrig*25/0.35)/22)/ ann_manure_tot ;

con_annperc_enercrop_totcrop.. perc_enercrop_totcrop =E= (((t_crop/0.098)/15.26 + (i_crop/0.163)/15.26 + (((n_gasifier_light*1000000)/21111)/3.6)*1.8 + (((d_gasifier_light*1000000)/21111)/3.6)*1.8 + (n_gasifier_power/3.6)*1.8 + (d_gasifier_power/3.6)*1.8) + ((gasifier_irrig/0.9) /3.6)*1.8) / tot_ann_cropres_nonliv;

con_annperc_enerwood_totwood.. perc_enerwood_totwood =E= ((t_wood/0.18)/19.71 + (i_wood/0.3)/19.71)/ tot_ann_forest ;

**** Defining different models***

Model BAU /
con_dung,
con_slurry,
con_dungforcrop,
con_manure,
con_wood,
con_cropres,
con_totcookdem,
con_grid_light_night,
con_grid_light_day,
con_tot_nightlight,
con_tot_daylight,
con_grid_power_day,
con_grid_power_night,
con_tot_daypower,
con_tot_nightpower,
con_tot_irrigation_energydemand,
con_healthcost,
con_co2emis,
con_cookenergy_price,
con_hhrevenue,
con_daypower_price,
con_nightpower_price,
con_daylight_price,
con_nightlight_price,
con_irrig_ener_price,
obj,
con_annperc_enerman_totman,

con_annperc_enercrop_totcrop,
con_annperc_enerwood_totwood/
;

Model BAUwithhealth /
con_dung,
con_slurry,
con_dungforcrop,
con_manure,
con_wood,
con_cropres,
con_totcookdem,
con_grid_light_night,
con_grid_light_day
con_tot_nightlight,
con_tot_daylight,
con_grid_power_day,
con_grid_power_night,
con_tot_daypower,
con_tot_nightpower,
con_tot_irrigation_energydemand,
con_healthcost,
con_co2emis,
con_cookenergy_price,
con_hhrevenue,
con_daypower_price,
con_nightpower_price,
con_daylight_price,
con_nightlight_price
con_irrig_ener_price,
obj_health,
con_annperc_enerman_totman,
con_annperc_enercrop_totcrop,
con_annperc_enerwood_totwood /
;

**** Executing the selected model***

solve BAU using LP minimizing v_obj;
*solve BAUwithhealth using LP minimizing v_obj;

**** Displaying the model results***

display t_dung.L , i_dung.L, t_wood.L , i_wood.L, t_crop.L, i_crop.L, lpg.L, bgas_cook.L, slurry_prod.L , n_ker_light.L, n_solbat_light.L, n_grid_light.L, n_gridbat_light.L, n_disgen_light.L , n_gasifier_light.L,n_biogas_light.L, d_ker_light.L, d_solbat_light.L, d_sol_light.L, d_grid_light.L, d_gridbat_light.L, d_disgen_light.L ,d_gasifier_light.L, d_biogas_light.L, d_sol_power.L , d_solbat_power.L , d_grid_power.L , d_gridbat_power.L , d_disgen_power.L, d_gasifier_power.L, d_bgas_power.L, n_solbat_power.L, n_grid_power.L , n_gridbat_power.L , n_disgen_power.L , n_gasifier_power.L, n_bgas_power.L , swp_irrig.L , dis_irrig.L , grid_irrig.L, tot_co2emis.L, v_obj.L, hh_revenue.L,cook_energy_price.L, day_power_price.L, night_power_price.L, day_light_price.L, night_light_price.L, irrig_ener_price.L, perc_enerman_totman.L, perc_enercrop_totcrop.L, perc_enerwood_totwood.L;

Appendix 4: Descriptive Statistics on poor and rich household

This appendix presents the household characteristics for both poor and rich households, where table A4.1 presents the descriptive statistics of poor households and Table A4.2 presents the same for rich households. The mean data for poor and rich household is inputted in the GAMS AHM model for poor and rich household respectively, along with the energy technology data from Appendix 1.

Table A4.1: Descriptive statistics of household data collected on poor households

Poor household					
S.No	Household charateristics	Mean	Std. Dev.	Min	Max
1	Household size (nos)	6.5	2.6	1.0	16.0
2	number of household males (nos)	2.0	1.1	0.0	5.0
3	number of household females (nos)	1.8	1.1	0.0	6.0
4	number of household children (nos)	2.3	1.8	0.0	9.0
5	farm size (acres)	0.9	1.0	0.0	6.5
6	wheat plot size (acres)	0.7	0.8	0.0	6.5
7	rice plot size (acres)	0.5	0.7	0.0	6.5
8	sugarcane plot size (acres)	0.1	0.2	0.0	2.3
9	mustard plot size (acres)	0.1	0.3	0.0	4.2
10	potato plot size (acres)	0.1	0.3	0.0	4.0
11	wheat output per acre (kgs/ acre)	1304.9	411.0	333.3	2666.7
12	rice output per acre (kgs/ acre)	1174.6	506.9	83.3	3200.0
13	sugarcane output per acre (kgs/ acre)	22545.1	5829.8	10333.3	40000.0
14	mustard output per acre (kgs/ acre)	351.2	134.7	50.0	700.0
15	potato output per acre (kgs/ acre)	7595.0	2296.0	2500.0	10625.0
16	wheat sale price (Rs/ kg)	13.5	0.9	11.0	16.0
17	rice sale price (Rs/ kg)	12.5	2.3	10.0	20.0
18	sugarcane sale price (Rs/ kg)	2.6	0.2	2.4	2.9
19	mustard sale price (Rs/ kg)	20.7	10.1	10.0	30.0
20	potato sale price (Rs/ kg)	8.8	3.3	5.0	16.0
21	hours per acre of irrigation for wheat crop (hrs/ acre)	25.0	8.1	0.0	51.4
22	hours per acre of irrigation for rice crop (hrs/ acre)	37.9	16.8	0.0	135.3
23	hours per acre of irrigation for sugarcane crop (hrs/ acre)	41.0	13.9	29.3	90.0
24	hours per acre of irrigation for mustard crop (hrs/ acre)	11.4	5.2	0.0	28.0
25	hours per acre of irrigation for potato crop (hrs/ acre)	20.5	8.3	9.0	40.0
26	Irrigation Energy required per acre for wheat crop (MJ/ acre)	225.9	73.2	0.0	464.8
27	Irrigation Energy required per acre for rice crop (MJ/ acre)	250.5	111.3	0.0	895.3

28	Irrigation Energy required per acre for sugarcane crop (MJ/ acre)	30.3	10.3	21.7	66.6
29	Irrigation Energy required per acre for mustard crop (MJ/ acre)	9.3	4.2	0.0	22.9
30	Irrigation Energy required per acre for potato crop (MJ/ acre)	15.6	6.3	6.8	30.4
31	dung fertilizer per acre of wheat crop (kg/ acre)	892.0	2124.5	0.0	16500.0
32	dung fertilizer per acre of rice crop (kg/ acre)	2192.5	1928.8	0.0	9900.0
33	dung fertilizer per acre of sugarcane crop (kg/ acre)	1644.7	1949.1	0.0	5910.4
34	dung fertilizer per acre of mustard crop (kg/ acre)	0.0	0.0	0.0	0.0
35	dung fertilizer per acre of potato crop (kg/ acre)	7525.3	3164.3	2955.2	13860.0
36	Input costs (without labor) for wheat, RS/acre	11857.2	3275.2	4472.2	24200.0
37	Input costs (without labor) for rice, RS/acre	10359.6	10295.4	2610.0	130980.0
38	Input costs (without labor) for sugarcane, RS/acre	17857.1	4201.5	11293.0	25276.7
39	Input costs (without labor) for mustard, RS/acre	6864.2	2976.9	3020.0	17824.2
40	Input costs (without labor) for potato, RS/acre	36888.5	13099.9	15400.0	63402.0
41	male labor days required per acre for wheat (days/ acre)	13.1	7.4	0.0	78.6
42	female labor days required per acre for wheat (days/ acre)	9.7	5.4	0.0	45.0
43	child labor days required per acre for wheat (days/ acre)	1.8	3.1	0.0	15.6
44	male labor days required per acre for rice (days/ acre)	18.6	13.5	1.4	114.3
45	female labor days required per acre for rice (days/ acre)	37.2	16.6	5.3	100.0
46	child labor days required per acre for rice (days/ acre)	4.3	6.6	0.0	33.3
47	male labor days required per acre for sugarcane (days/ acre)	47.9	13.1	28.3	74.8
48	female labor days required per acre for sugarcane (days/ acre)	14.7	14.9	0.0	53.3
49	child labor days required per acre for sugarcane (days/ acre)	3.6	6.6	0.0	18.6
50	male labor days required per acre for mustard (days/ acre)	18.2	12.1	0.0	57.0
51	female labor days required per acre for mustard (days/ acre)	23.0	16.4	0.0	80.0
52	child labor days required per acre for mustard (days/ acre)	1.7	6.5	0.0	40.0
53	male labor days required per acre for potato (days/ acre)	30.0	19.1	7.0	61.0
54	female labor days required per acre for potato (days/ acre)	36.8	21.3	15.0	80.0
55	child labor days required per acre for potato (days/ acre)	21.1	31.7	0.0	120.0
56	number of buffalos per hh (numbers / hh)	0.6	0.9	0.0	6.0
57	number of cows per hh (numbers / hh)	0.5	0.7	0.0	3.0
58	milk yield of cow (liters/ head/ month)	103.0	20.5	60.0	150.0

59	milk yield of buffalo (liters/ head/ month)	110.9	22.2	60.0	220.0
60	manure yield of female cow (liters/ head/ year)	552.7	29.2	400.0	700.0
61	manure yield of female buffalo (liters/ head/ year)	602.0	15.8	500.0	650.0
62	market price of female cow per head (Rs/ head)	21395.6	3165.4	15000.0	40000.0
63	market price of female buffalo per head (Rs/ head)	32306.1	7105.1	25000.0	80000.0
64	sale price of cow milk (Rs/ liter)	26.4	2.4	25.0	32.0
65	sale price of buffalo milk (Rs/ liter)	33.0	3.5	25.0	40.0
66	sale price of livestock manure (Rs/ kg)	0.5			
67	milk yield of female cow (liters/ head/ year)	1235.6	245.9	720.0	1800.0
68	milk yield of female buffalo (liters/ head/ year)	1331.2	266.9	720.0	2640.0
69	monthly wheat feed per female cow (kgs/ month/ head)	13.2	8.1	0.0	40.0
70	monthly barley feed per female cow (kgs/ month/ head)	1.8	4.5	0.0	16.3
71	monthly mustard cake feed per female cow (kgs/ month/ head)	5.9	5.6	0.0	20.0
72	monthly wheat straw or rice straw feed per female cow (kgs/ month/ head)	119.3	18.6	40.0	200.0
73	monthly sorghum or trifolium or sugarcane top feed per female cow (kgs/ month/ head)	61.5	89.5	0.0	350.0
74	monthly wheat feed per female buffalo (kgs/ month/ head)	21.0	10.5	0.0	70.0
75	monthly barley feed per female buffalo (kgs/ month/ head)	3.0	6.3	0.0	20.0
76	monthly mustard cake feed per female buffalo (kgs/ month/ head)	9.9	8.1	0.0	35.0
77	monthly wheat straw or rice straw feed per female buffalo (kgs/ month/ head)	166.4	27.6	75.0	240.0
78	monthly sorghum or trifolium or sugarcane top feed per female buffalo (kgs/ month/ head)	143.7	159.4	0.0	600.0
79	annual off-farm male agricultural days (days/ year)	19.5	37.1	0.0	320.0
80	annual off-farm female agricultural days (days/ year)	23.5	31.2	0.0	155.0
81	annual off-farm child agricultural days (days/ year)	6.0	19.7	0.0	156.0
82	annual non-agricultural male work days (days/ year)	275.3	193.9	0.0	1120.0
83	annual non-agricultural female work days (days/ year)	22.0	47.0	0.0	320.0
84	annual non-agricultural child work days (days/ year)	5.6	26.8	0.0	300.0
85	off-farm male wage of construction labor (Rs/day)	246.7	60.5	150.0	500.0
86	off-farm male wage of other non-agricultural labor such as NAREGA (Rs/day)	176.4	58.3	40.0	500.0
87	off-farm male salary wage (Rs/day)	211.9	127.6	60.0	709.7
88	off-farm male business wage (Rs/day)	170.0	103.3	42.0	468.8
89	average off-farm male non agricultural work wage (Rs/ day)	201.3			
90	off-farm female wage of other non-agricultural labor such as NAREGA (Rs/day)	137.5	34.6	12.0	156.0

91	off-farm female salary wage (Rs/day)	124.5	107.5	60.0	360.0
92	off-farm female business wage (Rs/day)	97.5	107.3	30.0	500.0
93	average off-farm female non agricultural work wage (Rs/ day)	119.8			
94	off-farm child non agricultural work wage (Rs/ day)	65.0	11.8	50.0	80.0
95	off-farm male agricultural wage (Rs/ day)	170.4	45.4	0.0	250.0
96	off-farm female agricultural wage (Rs/ day)	117.4	40.0	20.0	200.0
97	off-farm child agricultural wage (Rs/ day)	121.7	36.0	50.0	180.0
98	monthly expenditure on edible oil purchase from market (Rs/ month)	311.3	142.2	0.0	800.0
99	monthlyexpenditure on milk purchase from market (Rs/ month)	170.2	343.6	0.0	2700.0
100	annual amount of dung cake used for cooking (kg/ year)	1643.5	902.3	0.0	4200.0
101	annual amount of firewood used for cooking (kg/ year)	1020.8	719.9	60.0	4560.0
102	annual amount of crop residues used for cooking (kg/ year)	194.8	306.0	0.0	2400.0
103	monthly amount of LPG used for cooking (kg)	3.0	4.9	0.0	18.0
104	annual number of hours spent by hh male for firewood collection (hours)	35.5	39.6	0.0	220.0
105	annual number of hours spent by hh female for firewood collection (hours)	76.7	79.5	0.0	420.0
106	annual number of hours spent by hh child for firewood collection (hours)	30.9	43.8	0.0	220.0
107	annual number of hours spent by hh male for crop residue collection (hours)	5.6	13.0	0.0	60.0
108	annual number of hours spent by hh female for crop residue collection (hours)	9.8	21.9	0.0	140.0
109	annual number of hours spent by hh child for crop residue collection (hours)	1.8	7.6	0.0	65.0
110	annual number of hours spent by hh female for cattle dung cake collection (hours)	227.7	154.4	0.0	720.0
111	annual number of hours spent by hh child for cattle dung cake collection (hours)	51.7	108.8	0.0	480.0
112	Monthly available electricity grid available for lighting in night (KwH/month)	14.2	15.1	0.0	75.0
113	Monthly available electricity grid available for electricity equipments (other then lighting) in night (KwH/month)	8.8	13.9	0.0	77.4
114	Monthly available electricity grid available for lighting in day time (KwH/month)	0.0	0.0	0.0	0.0
115	Monthly available electricity grid available for electricity equipments (other then lighting) in day time (KwH/month)	11.4	19.7	0.0	97.9
116	monthly kerosene lighting energy used (MJ/mo)	109.1	39.6	0.0	305.5
117	monthly LPG lighting used (MJ/mo)	2.0	8.6	0.0	45.6
118	monthly diesel electricity used (MJ/mo)	0.3	3.3	0.0	50.4
119	monthly renewable electricity used (MJ/mo)	1.7	11.8	0.0	162.0

120	monthly battery electricity used (MJ/mo)	5.4	22.9	0.0	129.6
121	Required monthly lighting energy in night (KwH/month)	39.5	42.2	0.0	210.0
122	Required monthly electricity (non-lighting) energy in night (KwH/month)	15.1	23.5	0.0	130.2
123	Required monthly electricity (non-lighting) energy in day time (KwH/month)	17.5	30.5	0.0	152.3
124	Annual Wheat consumption from own produce (kgs)	501.6	483.8	0.0	2400.0
125	Annual Rice consumption from own produce (kgs)	325.4	372.3	0.0	1500.0
126	Annual Sugarcane consumption from own produce (kgs)	51.1	348.8	0.0	4000.0
127	Annual Mustard consumption from own produce (kgs)	15.5	45.7	0.0	400.0
128	Annual Potato consumption from own produce (kgs)	41.0	219.2	0.0	2000.0
129	Annual Milk consumption from own produce (kgs)	617.5	763.1	0.0	10440.0
130	Annual market purchase of wheat (kgs)	190.7	212.7	0.0	1600.0
131	Annual market purchase of rice (kgs)	192.9	151.0	0.0	800.0
132	Monthly edible oil purchase (Rs)	311.3	142.2	0.0	800.0
133	Annual household revenues (Rs/ year)	112584.0	49098.2	11900.0	221860.0

Table A4.2: Descriptive statistics of household data collected on rich households

Rich household					
S.No	Household charateristics	Mean	Std. Dev.	Min	Max
1	Household size (nos)	7.8	3.5	3.0	18.0
2	number of household males (nos)	2.7	1.4	1.0	7.0
3	number of household females (nos)	2.3	1.3	1.0	6.0
4	number of household children (nos)	2.3	2.1	0.0	10.0
5	farm size (acres)	4.0	6.3	0.0	57.3
6	wheat plot size (acres)	2.0	2.3	0.0	20.0
7	rice plot size (acres)	1.1	1.8	0.0	10.0
8	sugarcane plot size (acres)	0.7	2.4	0.0	18.0
9	mustard plot size (acres)	0.1	0.3	0.0	1.3
10	potato plot size (acres)	1.0	2.2	0.0	18.0
11	wheat output per acre (kgs/ acre)	1514.3	363.9	666.7	2253.5
12	rice output per acre (kgs/ acre)	1307.7	507.7	365.6	2500.0
13	sugarcane output per acre (kgs/ acre)	24226.2	5599.1	14583.3	35000.0
14	mustard output per acre (kgs/ acre)	380.2	122.5	175.0	750.0
15	potato output per acre (kgs/ acre)	10524.8	2217.5	6666.7	15000.0
16	wheat sale price (Rs/ kg)	13.8	0.9	12.0	16.0
17	rice sale price (Rs/ kg)	14.2	6.1	8.0	40.0
18	sugarcane sale price (Rs/ kg)	2.7	0.2	2.4	2.8
19	mustard sale price (Rs/ kg)	25.8	11.2	3.0	31.0
20	potato sale price (Rs/ kg)	11.1	4.3	5.0	18.0

21	hours per acre of irrigation for wheat crop (hrs/ acre)	28.9	7.9	6.0	42.4
22	hours per acre of irrigation for rice crop (hrs/ acre)	43.6	18.5	13.6	91.0
23	hours per acre of irrigation for sugarcane crop (hrs/ acre)	50.6	23.1	16.7	100.0
24	hours per acre of irrigation for mustard crop (hrs/ acre)	12.0	6.2	0.0	27.6
25	hours per acre of irrigation for potato crop (hrs/ acre)	20.9	6.9	10.0	36.0
26	Irrigation Energy required per acre for wheat crop (MJ/ acre)	746.2	203.7	154.1	1093.0
27	Irrigation Energy required per acre for rice crop (MJ/ acre)	591.2	250.9	185.1	1235.0
28	Irrigation Energy required per acre for sugarcane crop (MJ/ acre)	424.8	194.1	140.0	840.0
29	Irrigation Energy required per acre for mustard crop (MJ/ acre)	21.5	11.0	0.0	49.4
30	Irrigation Energy required per acre for potato crop (MJ/ acre)	261.4	86.0	125.4	451.4
31	dung fertilizer per acre of wheat crop (kg/ acre)	1006.5	1710.1	0.0	9900.0
32	dung fertilizer per acre of rice crop (kg/ acre)	2273.8	1627.8	0.0	7425.0
33	dung fertilizer per acre of sugarcane crop (kg/ acre)	2543.9	2188.4	0.0	5910.4
34	dung fertilizer per acre of mustard crop (kg/ acre)	309.4	1750.1	0.0	9900.0
35	dung fertilizer per acre of potato crop (kg/ acre)	7545.2	3333.1	2076.9	13894.7
36	Input costs (without labor) for wheat, RS/acre	12794.8	3026.1	6711.4	22890.0
37	Input costs (without labor) for rice, RS/acre	10496.5	2524.2	5544.0	15901.4
38	Input costs (without labor) for sugarcane, RS/acre	18669.3	4777.7	11468.1	31130.0
39	Input costs (without labor) for mustard, RS/acre	7112.7	3247.0	3978.2	18769.2
40	Input costs (without labor) for potato, RS/acre	40157.6	10179.4	23070.2	67984.0
41	male labor days required per acre for wheat (days/ acre)	11.4	5.5	3.0	31.5
42	female labor days required per acre for wheat (days/ acre)	8.2	4.7	0.0	26.7
43	child labor days required per acre for wheat (days/ acre)	0.9	1.9	0.0	10.6
44	male labor days required per acre for rice (days/ acre)	11.7	10.0	0.8	46.3
45	female labor days required per acre for rice (days/ acre)	33.2	17.4	2.0	86.7
46	child labor days required per acre for rice (days/ acre)	2.6	3.5	0.0	16.0
47	male labor days required per acre for sugarcane (days/ acre)	40.1	10.7	17.8	59.6

48	female labor days required per acre for sugarcane (days/ acre)	14.1	11.2	0.0	30.3
49	child labor days required per acre for sugarcane (days/ acre)	0.4	1.1	0.0	4.8
50	male labor days required per acre for mustard (days/ acre)	13.1	8.1	3.0	35.8
51	female labor days required per acre for mustard (days/ acre)	15.0	12.4	0.0	40.0
52	child labor days required per acre for mustard (days/ acre)	0.2	0.9	0.0	5.0
53	male labor days required per acre for potato (days/ acre)	14.3	11.2	4.2	58.3
54	female labor days required per acre for potato (days/ acre)	23.5	9.5	14.1	53.3
55	child labor days required per acre for potato (days/ acre)	10.9	4.6	0.0	20.0
56	number of buffalos per hh (numbers / hh)	1.5	1.5	0.0	6.0
57	number of cows per hh (numbers / hh)	0.9	1.3	0.0	6.0
58	milk yield of cow (liters/ head/ month)	120.6	45.9	45.0	400.0
59	milk yield of buffalo (liters/ head/ month)	131.1	22.2	60.0	180.0
60	manure yield of female cow (liters/ head/ year)	568.3	43.2	450.0	650.0
61	manure yield of female buffalo (liters/ head/ year)	608.1	28.4	488.0	700.0
62	market price of female cow per head (Rs/ head)	24538.5	7905.0	18000.0	70000.0
63	market price of female buffalo per head (Rs/ head)	39670.7	9204.2	20000.0	70000.0
64	sale price of cow milk (Rs/ liter)	28.0	3.1	25.0	32.0
65	sale price of buffalo milk (Rs/ liter)	33.8	3.3	30.0	40.0
66	sale price of livestock manure (Rs/ kg)	0.5			
67	milk yield of female cow (liters/ head/ year)	1447.7	551.3	540.0	4800.0
68	milk yield of female buffalo (liters/ head/ year)	1573.5	266.3	720.0	2160.0
69	monthly wheat feed per female cow (kgs/ month/ head)	20.7	9.8	7.5	70.0
70	monthly barley feed per female cow (kgs/ month/ head)	4.7	7.1	0.0	20.0
71	monthly mustard cake feed per female cow (kgs/ month/ head)	13.3	5.7	0.0	25.0
72	monthly wheat straw or rice straw feed per female cow (kgs/ month/ head)	124.3	27.2	80.0	200.0
73	monthly sorghum or trifolium or sugarcane top feed per female cow (kgs/ month/ head)	125.4	109.8	0.0	400.0
74	monthly wheat feed per female buffalo (kgs/ month/ head)	31.2	13.2	10.0	75.0
75	monthly barley feed per female buffalo (kgs/ month/ head)	8.2	9.4	0.0	35.0
76	monthly mustard cake feed per female buffalo (kgs/ month/ head)	18.7	8.1	0.0	31.3

77	monthly wheat straw or rice straw feed per female buffalo (kgs/ month/ head)	173.3	37.1	80.0	300.0
78	monthly sorghum or trifolium or sugarcane top feed per female buffalo (kgs/ month/ head)	211.2	140.7	0.0	600.0
79	annual off-farm male agricultural days (days/ year)	10.3	28.7	0.0	180.0
80	annual off-farm female agricultural days (days/ year)	11.0	31.6	0.0	200.0
81	annual off-farm child agricultural days (days/ year)	1.1	7.7	0.0	60.0
82	annual non-agricultural male work days (days/ year)	357.7	327.2	0.0	1240.0
83	annual non-agricultural female work days (days/ year)	13.8	56.5	0.0	393.0
84	annual non-agricultural child work days (days/ year)	1.6	9.8	0.0	70.0
85	off-farm male wage of construction labor (Rs/day)	254.4	43.5	200.0	400.0
86	off-farm male wage of other non-agricultural labor such as NAREGA (Rs/day)	165.8	23.8	150.0	200.0
87	off-farm male salary wage (Rs/day)	569.0	473.0	80.0	2400.0
88	off-farm male business wage (Rs/day)	461.3	361.0	41.7	1500.0
89	average off-farm male non agricultural work wage (Rs/ day)	362.6			
90	off-farm female wage of other non-agricultural labor such as NAREGA (Rs/day)	152.7	3.2	150.0	156.0
91	off-farm female salary wage (Rs/day)	87.9	60.9	16.4	150.0
92	off-farm female business wage (Rs/day)				
93	average off-farm female non agricultural work wage (Rs/ day)	120.3			
94	off-farm child non agri. work wage (Rs/ day)	60.0	10.0	50.0	70.0
95	off-farm male agricultural wage (Rs/ day)	217.5	46.7	150.0	300.0
96	off-farm female agricultural wage (Rs/ day)	155.0	39.7	50.0	200.0
97	off-farm child agricultural wage (Rs/ day)	186.7	11.5	180.0	200.0
98	monthly expenditure on edible oil purchase from market (Rs/ month)	335.7	231.0	0.0	1200.0
99	monthlyexpenditure on milk purchase from market (Rs/ month)	188.1	410.7	0.0	1800.0
100	annual amount of dung cake used for cooking (kg/ year)	1932.1	1281.7	0.0	6000.0
101	annual amount of firewood used for cooking (kg/ year)	923.7	593.8	180.0	2880.0
102	annual amount of crop residues used for cooking (kg/ year)	109.2	229.3	0.0	1110.0
103	monthly amount of LPG used for cooking (kg)	8.4	7.6	0.0	42.0
104	annual number of hours spent by hh male for firewood collection (hours)	20.8	28.3	0.0	140.0
105	annual number of hours spent by hh female for firewood collection (hours)	31.9	66.7	0.0	440.0

106	annual number of hours spent by hh child for firewood collection (hours)	10.7	24.2	0.0	100.0
107	annual number of hours spent by hh male for crop residue collection (hours)	1.5	7.4	0.0	45.0
108	annual number of hours spent by hh female for crop residue collection (hours)	2.3	11.7	0.0	85.0
109	annual number of hours spent by hh child for crop residue collection (hours)	0.1	1.4	0.0	15.0
110	annual number of hours spent by hh female for cattle dung cake collection (hours)	249.0	214.3	0.0	720.0
111	annual number of hours spent by hh child for cattle dung cake collection (hours)	35.9	98.0	0.0	480.0
112	Monthly available electricity grid available for lighting in night (KwH/month)	26.8	17.6	0.0	75.0
113	Monthly available electricity grid available for electricity equipments (other then lighting) in night (KwH/month)	39.1	40.0	0.0	247.3
114	Monthly available electricity grid available for lighting in day time (KwH/month)	0.0	0.0	0.0	0.0
115	Monthly available electricity grid available for electricity equipments (other then lighting) in day time (KwH/month)	57.6	63.2	0.0	323.9
116	monthly kerosene lighting energy used (MJ/mo)	104.3	59.7	0.0	267.3
117	monthly LPG lighting used (MJ/mo)	7.0	15.2	0.0	68.3
118	monthly diesel electricity used (MJ/mo)	5.7	17.4	0.0	108.0
119	monthly renewable electricity used (MJ/mo)	6.0	24.4	0.0	162.0
120	monthly battery electricity used (MJ/mo)	42.8	70.3	0.0	194.4
121	Required monthly lighting energy in night (KwH/month)	74.7	49.3	0.0	210.0
122	Required monthly electricity (non-lighting) energy in night (KwH/month)	65.6	65.6	0.0	402.6
123	Required monthly electricity (non-lighting) energy in day time (KwH/month)	85.0	90.6	0.0	459.6
124	Annual Wheat consumption from own produce (kgs)	1171.3	789.7	0.0	4000.0
125	Annual Rice consumption from own produce (kgs)	363.5	507.5	0.0	2000.0
126	Annual Sugarcane consumption from own produce (kgs)	297.3	1940.6	0.0	20000.0
127	Annual Mustard consumption from own produce (kgs)	41.0	80.6	0.0	400.0
128	Annual Potato consumption from own produce (kgs)	762.3	2266.4	0.0	20000.0
129	Annual Milk consumption - own produce (kgs)	1313.4	837.0	120.0	4920.0
130	Annual market purchase of wheat (kgs)	147.8	396.6	0.0	2500.0
131	Annual market purchase of rice (kgs)	94.4	144.8	0.0	1000.0
132	Monthly edible oil purchase (Rs)	335.7	231.0	0.0	1200.0
133	Annual household revenues (Rs/ year)	490276.5	412684.8	225000.0	3196160.0

Appendix 5: GAMS model: Agricultural household model with its interaction to Village Energy System (VES)

This appendix presents the GAMS model that has been written to formulate an agricultural household model with its linkages to the Village Energy System (VES). The objective of this model is the maximization of the annual household income (discounted annual net present value) over 15 years period. This is for the rich household in VES scenario. The model for the poor household in VES scenario will be same but with the corresponding data for the poor household. Similarly, models for BAU scenario will be same but the parameters regarding VES energy services such as price and possible energy input will be 0.

Declaration and definition of variables in the model

```
free variable v_obj       Annual household income (discounted annual net present value considering
15 years period)

;

integer variable
v_live_cow        Heads of cows after sale and purchase at the end of each year (nos)
v_live_buffalo    Heads of buffalos after sale and purchase at the end of each year (nos)
;

positive variable
v_rice_sale           amount of rice sold per year (kg per year)
v_wheat_sale          amount of wheat sold per year (kg per year)
v_sugar_sale          amount of sugar sold per year (kg per year)
v_mustard_sale        amount of nustard sold per year (kg per year)
v_potato_sale         amount of potato sold per year (kg per year)
v_rhusk_sale          amount of rice husk sold per year (kg per year)
v_rhusk_mg            amount of rice husk sold to mini grid per year (kg per year)
v_rstraw_sale         amount of rice straw sold per year (kg per year)
v_wstraw_sale         amount of wheat husk sold per year (kg per year)
v_stop_sale           amount of sugarcane top sold per year (kg per year)
v_sleaves_sale        amount of sugarcane leaves sold per year (kg per year)
v_sleaves_mg          amount of sugarcane leaves sold to mini grid per year (kg per year)
v_mstraw_sale         amount of mustard straw sold per year (kg per year)
v_mcake_sale          amount of mustard cake sold per year (kg per year)
v_cowmilk_sale        amount of cow milk sold per year (liters per year)
v_cowmanure_sale      amount of cow manure sold per year (kgs per year)
v_bufmilk_sale        amount of buffalo milk sold per year (liters per year)
v_bufmanure_sale      amount of buffalo manure sold per year (kgs per year)
v_cow_headsale        cow heads sold per year (numbers)
v_buf_headsale        buffalo heads sold per year (numbers)
```

v_nonagrilab_male   Annual number of male off farm non agricultural labor (days per year)
v_nonagrilab_female   Annual number of female off farm non agricultural labor (days per year)
v_nonagrilab_child   Annual number of child off farm non agricultural labor (days per year)
v_farmlabout_male   annual off farm agri male labor days (days per year)
v_farmlabout_female annual off farm agri female labor days (days per year)
v_farmlabout_child   annual off farm agri child labor days (days per year)
v_farmlabin_male   annual off farm agri outside male labor days hired for households' field (days per year)
v_farmlabin_female annual off farm agri outside female labor days hired for households' field (days per year)
v_farmlabin_child   annual off farm agri outside child labor days hired for households' field (days per year)
v_rice_area   Area of rice crop grown per year (acres)
v_wheat_area   Area of wheat crop grown per year (acres)
v_sugar_area   Area of sugarcane crop grown per year (acres)
v_mustard_area   Area of mustard crop grown per year (acres)
v_potato_area   Area of potato crop grown per year (acres)
v_rice_buy   Amount of rice purchased from market in year (kgs per year)
v_wheat_buy   Amount of wheat purchased from market in year (kgs per year)
v_sugar_buy   Amount of sugarcane purchased from market in year (kgs per year)
v_mustard_buy   Amount of mustard purchased from market in year (kgs per year)
v_potato_buy   Amount of potato purchased from market in year (kgs per year)
v_rhusk_buy   Amount of rice husk bought from market in a year (kgs per year)
v_rstraw_buy   Amount of rice straw bought from market in a year (kgs per year)
v_wstraw_buy   Amount of wheat straw bought from market in a year (kgs per year)
v_stop_buy   Amount of sugarcane top bought from market in a year (kgs per year)
v_sleaves_buy   Amount of sugarcane leaves bought from market in a year (kgs per year)
v_mstraw_buy   Amount of mustard straw bought from market in a year (kgs per year)
v_mcake_buy   Amount of mustard cake bought from market in a year (kgs per year)
v_cowmilk_buy   Amount of cow milk bought per year (liters per year)
v_cowmanure_buy Amount of cow manure bought per year (kgs per year)
v_bufmilk_buy   Amount of buffalo milk bought per year (liters per year)
v_bufmanure_buy Amount of buffalo manure bought per year (liters per year)
v_cow_headbuy   Heads of cows bought in a year (heads per year)
v_buf_headbuy   Heads of buffalos bought in a year (heads per year)
t_dung   useful annual energy taken from dung cake burnt in traditional cookstove (MJ per year)
i_dung   useful annual energy taken from dung cake burnt in improved cookstove (MJ per year)
t_wood   useful annual energy taken from wood burnt in traditional cookstove (MJ per year)
i_wood   useful annual energy taken from wood burnt in improved cookstove (MJ per year)
t_crop   useful annual energy taken from crop residue burnt in traditional cookstove (MJ per year)
i_crop   useful annual energy taken from crop residues burnt in improved cookstove (MJ per year)
lpg   useful annual energy taken from lpg burnt in lpg stove (MJ per year)
bgas_cook   useful annual energy taken from biogas burnt in biogas cookstove (MJ per year)

slurry_prod annual amount of slurry produced by biogas production (Kg per year)
n_ker_light million lumen hours per year received from kerosene for lighting in night (m lumenhours per year)
n_solbat_light million lumen hours per year received from LED-solar plus battery for lighting in night (m lumenhours per year)
n_grid_light million lumen hours per year received from LED-grid electricity for lighting in night (m lumenhours per year)
n_gridbat_light million lumen hours per year received from LED-grid electricity-battery for lighting in night (m lumenhours per year)
n_disgen_light million lumen hours per year received from LED-diesel genset for lighting in night (m lumenhours per year)
n_biogas_light million lumen hours per year received from biogas mantle for lighting in night (m lumenhours per year)
n_LPG_light million lumen hours per year received from LPG mantle for lighting in night (m lumenhours per year)
d_ker_light million lumen hours per year received from kerosene for lighting in day (m lumenhours per year)
d_solbat_light million lumen hours per year received from LED-solar plus battery for lighting in day (m lumenhours per year)
d_grid_light million lumen hours per year received from LED-grid electricity for lighting in day (m lumenhours per year)
d_gridbat_light million lumen hours per year received from LED-grid electricity-battery for lighting in day (m lumenhours per year)
d_disgen_light million lumen hours per year received from LED-diesel genset for lighting in day (m lumenhours per year)
d_biogas_light million lumen hours per year received from biogas mantle for lighting in day (m lumenhours per year)
d_LPG_light million lumen hours per year received from LPG mantle for lighting in day (m lumenhours per year)
d_sol_light million lumen hours per year received from solar for lighting in day (m lumenhours per year)
n_solbat_power Annual useful electricity taken from solar plus battery for non lighting electrcity in night(MJ per year)
n_grid_power Annual useful electricity taken from grid for non lighting electrcity in night(MJ per year)
n_gridbat_power Annual useful electricity taken from grid plus battery for non lighting electrcity in night(MJ per year)
n_disgen_power Annual useful electricity taken from diesel genset for non lighting electrcity in night(MJ per year)
n_bgas_power Annual useful electricity taken from biogas for non lighting electrcity in night(MJ per year)
d_sol_power Annual useful electricity taken from solar for non lighting electrcity in day(MJ per year)
d_solbat_power Annual useful electricity taken from solar plus battery for non lighting electrcity in day(MJ per year)

d_grid_power Annual useful electricity taken from grid electricity for non lighting electrcity in day(MJ per year)
d_gridbat_power Annual useful electricity taken from grid plus battery for non lighting electrcity in day(MJ per year)
d_disgen_power Annual useful electricity taken from diesel genset for non lighting electrcity in day(MJ per year)
d_bgas_power Annual useful electricity taken from biogas for non lighting electrcity in day(MJ per year)
swp_irrig Annual useful energy taken from solar water pump for irrigation (MJ per year)
dis_irrig Annual useful energy taken from diesel engine based pump for irrigation(MJ per year)
grid_irrig Annual useful energy taken from grid electricity tubewell for irrigation(MJ per year)
marketwater_irrig Annual useful market purchased irrigation (MJ per year)
bgas_irrig Annual useful energy taken from biogas based pump for irrigation(MJ per year)
tot_ann_cropres_nonliv Annual amount of crop residues (different types)which are used for energy purposes (kgs per year)
ann_manure_noncrop Annual amount (kg) of manure used for non crops such as energy sale discard etc
cook_energy_price Cooking energy price per MJ (Rs per MJ)
tot_healthcost total health damage costs because of CO and PM emissions of the energy system per year
tot_co2emis tonnes of CO2 emission per year associated with the energy system
hh_revenue Annual Household revenues
day_power_price price per unit of power in day time (Rs per MJ)
night_power_price price per unit of power in night time (Rs per MJ)
day_light_price price per unit of light in day time (Rs per million lumen hours
night_light_price price per unit of light in night time (Rs per million lumen hours
irrig_ener_price price per unit of irrigation in day time (Rs per MJ)
ann_manure_crop Annual amount (kg) of manure used for crops
v_enercook_mg cooking energy purchased from mini grid (MJ)
v_dlight_mg day time lighting purchased from mini grid (million lumen hours)
v_nlight_mg night time lighting purchased from mini grid (million lumen hours)
v_dpower_mg day time power purchased from mini grid (MJ)
v_npower_mg night time power purchased from mini grid (MJ)
v_irrig_mg irrigation energy purchased from mini grid (MJ)
v_budg Amount of budget per family per year (Rs per year)
v_labrice_male Annual male labor days for rice crop (days per year)
v_labwheat_male Annual male labor days for wheat crop (days per year)
v_labsugar_male Annual male labor days for sugar crop (days per year)
v_labmustard_male Annual male labor days for mustard crop (days per year)
v_labpotato_male Annual male labor days for potato crop (days per year)
v_labliv_male_cow Annual male labor days for cow rearing excluding dung preparation (days per year)
v_labliv_male_buffalo Annual male labor days for buffalo rearing excluding dung preparation (days per year)
v_labbp_male_rstraw Annual male labor days for energy production from rice straw (days per year)

v_labbp_male_sleaves Annual male labor days for energy production from sugarcane leaves (days per year)
v_labbp_male_mstraw Annual male labor days for energy production from mustard straw (days per year)
v_labdngcake_male Annual male labor days for energy production from dung cake (days per year)
v_labbgas_male Annual male labor days for energy production from biogas (days per year)
v_labenwood_male Annual male labor days for fuel wood production (days per year)
v_labrice_female Annual female labor days for rice crop (days per year)
v_labwheat_female Annual female labor days for wheat crop (days per year)
v_labsugar_female Annual female labor days for sugar crop (days per year)
v_labmustard_female Annual female labor days for mustard crop (days per year)
v_labpotato_female Annual female labor days for potato crop (days per year)
v_labliv_female_cow Annual female labor days for cow rearing excluding dung preperation (days per year)
v_labliv_female_buffalo Annual female labor days for buffalo rearing excluding dung preperation (days per year)
v_labbp_female_rstraw Annual female labor days for energy production from rice straw (days per year)
v_labbp_female_sleaves Annual female labor days for energy production from sugarcane leaves (days per year)
v_labbp_female_mstraw Annual female labor days for energy production from mustard straw (days per year)
v_labdngcake_female Annual female labor days for energy production from dung cake (days per year)
v_labbgas_female Annual female labor days for energy production from biogas (days per year)
v_labenwood_female Annual female labor days for fuel wood production (days per year)
v_labrice_child Annual child labor days for rice crop (days per year)
v_labwheat_child Annual child labor days for wheat crop (days per year)
v_labsugar_child Annual child labor days for sugar crop (days per year)
v_labmustard_child Annual child labor days for mustard crop (days per year)
v_labpotato_child Annual child labor days for potato crop (days per year)
v_labliv_child_cow Annual child labor days for cow rearing excluding dung preperation (days per year)
v_labliv_child_buffalo Annual child labor days for buffalo rearing excluding dung preperation (days per year)
v_labbp_child_rstraw Annual child labor days for energy production from rice straw (days per year)
v_labbp_child_sleaves Annual child labor days for energy production from sugarcane leaves (days per year)
v_labbp_child_mstraw Annual child labor days for energy production from mustard straw (days per year)
v_labdngcake_child Annual child labor days for energy production from dung cake (days per year)
v_labbgas_child Annual child labor days for energy production from biogas (days per year)
v_labenwood_child Annual child labor days for fuel wood production (days per year)
v_farmlabout_child Annual hh child labour of household hired by other hhs for agricultural purposes (days per year)

v_enbp_rhusk Annual amount of rice husk used for energy purposes (kgs per year)
v_enbp_rstraw Annual amount of rice straw used for energy purposes (kgs per year)
v_enbp_sleaves Annual amount of sugarcane leaves used for energy purposes (kgs per year)
v_enbp_mstraw Annual amount of mustard straw used for energy purposes (kgs per year)
v_enbp_stop Annual amount of sugarcane leaves used for energy purposes (kgs per year)
v_enbp_wstraw Annual amount of mustard straw used for energy purposes (kgs per year)
v_enbp_mcake Annual amount of mustard cake used for energy purposes (kgs per year)
v_dungcake Annual amount of dung cake used for energy purposes (kgs per year)
v_bgas Annual amount of biogas used for energy purposes (m3 per year)
v_wood Annual amount of wood used for energy purposes (kg per year)
v_frmanur_wheat Annual requirement of manure for wheat crop (kgs per year)
v_frmanur_rice Annual requirement of manure for rice crop (kgs per year)
v_frmanur_sugar Annual requirement of manure for sugar crop (kgs per year)
v_frmanur_mustard Annual requirement of manure for mustard crop (kgs per year)
v_frmanur_potato Annual requirement of manure for potato crop (kgs per year)
v_labbp_male_energy Annual HH male labor for energy (days per year)
v_tot_ener_expense Annual total energy expenditure (Rs)
v_wood_sale amount of wood sold per year (kgs per year)
v_wood_buy amount of wood bought per year (kgs per year)
v_wood amount of wood used per year for energy purposes (kgs per year)
cook_energy_price average price of cooking from the usage of different cooking energy types (Rs per MJ)
day_power_price average price of power in day time from the usage of different power types (Rs per MJ)
night_power_price average price of power in night time from the usage of different power types (Rs per MJ)
night_light_price average price of light in night time from the usage of different lighting types (Rs per million lumen hours)
irrig_ener_price average price of irrigation from the usage of different irrigation types (Rs per MJ)
;

**** Household data and VES parameters which are input in the model***

Parameters rice_price rice price per kg (Rs per kg 14.2 13.07)
;
rice_price = 13.07
;
Parameters wheat_price wheat price per kg (Rs per kg 13.8)
;
wheat_price = 13.6
;
Parameters sugar_price sugar price per kg (Rs per kg 2.65)
;
sugar_price = 2.6
;
Parameters mustard_price mustard price per kg (Rs per kg 25.8)
;

```
mustard_price = 24.1
;
Parameters  potato_price  potato price per kg  (Rs per kg 11)
;
potato_price  =  10.4
;
Parameters  rhusk_price rice husk price per kg  (Rs per kg)
;
rhusk_price  =  2.5
;
Parameters  rstraw_price rice straw  price per kg  (Rs per kg)
;
rstraw_price  =  0.9
;
Parameters  wstraw_price wheat straw price per kg  (Rs per kg)
;
wstraw_price =  3.5
;
Parameters  stop_price  sugartop price  per kg  (Rs per kg)
;
stop_price =  0.5
;
Parameters  sleaves_price sugarcane leaves price  per kg  (Rs per kg)
;
sleaves_price =  0.5
;
Parameters  mstraw_price mustard straw price per kg  (Rs per kg)
;
mstraw_price =  4
;
Parameters  mcake_price mustard cake price per kg  (Rs per kg)
;
mcake_price =  16
;
Parameters  cowmilk_price cow milk price per liter  (Rs per liter)
;
cowmilk_price =  28
;
Parameters  cowmanure_price cow manure price per kg  (Rs per kg )
;
cowmanure_price =  0.5
;
Parameters  bufmilk_price  buffalo milk price per liter  (Rs per liter)
;
bufmilk_price =  33.8
;
Parameters  bufmanure_price  buffalo manure price per kg  (Rs per kg)
;
bufmanure_price =  0.5
;
Parameters  cow_price  cow price per head  (Rs per head) in NPV
```

```
;
cow_price =  22307
;
Parameters  buf_price  buffalo price per head  (Rs per head) in NPV
;
buf_price =  36063
;
Parameters  jobwag_male  off farm non agricultural job wage of male  (Rs per day)
;
jobwag_male =  360
;
Parameters  jobwag_female  off farm non agricultural job wage of female  (Rs per day)
;
jobwag_female  =  120
;
Parameters  jobwag_child   off farm non agricultural job wage of child  (Rs per day)
;
jobwag_child   =  64
;
Parameters  farmwage_male  off farm agricultural job wage of male  (Rs per day)
;
farmwage_male =  217
;
Parameters  farmwage_female  off farm agricultural job wage of female  (Rs per day)
;
farmwage_female  =  155
;
Parameters  farmwage_child    off farm agricultural job wage of child  (Rs per day)
;
farmwage_child   =  125
;
Parameters  rice_costinp  input costs of rice crop per acre  (Rs per acre)
;
rice_costinp =  10500
;
Parameters  wheat_costinp  input costs of wheat crop per acre  (Rs per acre)
;
wheat_costinp =  12794
;
Parameters  sugar_costinp  input costs of sugarcane crop per acre  (Rs per acre)
;
sugar_costinp =  18669
;
Parameters  mustard_costinp  input costs of mustard crop per acre  (Rs per acre)
;
mustard_costinp =  7112
;
Parameters  potato_costinp  input costs of potato crop per acre  (Rs per acre)
;
potato_costinp =  40157
;
```

```
Parameters  p_tdung     levelized cost of useful enrgy from dung cake in traditional stove (Rs per MJ)
;
p_tdung=0
;
Parameters  p_idung    levelized cost of useful enrgy from dung cake in improved stove (Rs per MJ)
;
p_idung=0.074
;
Parameters  p_twood   levelized cost of useful enrgy from wood in traditional stove (Rs per MJ)
;
p_twood=0
;
Parameters  p_iwood   levelized cost of useful enrgy from wood in improved stove (Rs per MJ )
;
p_iwood= 0.023
;
Parameters  p_tcrop  levelized cost of useful enrgy from crop residue in traditional stove (Rs per MJ)
;
p_tcrop=0
;
Parameters  p_icrop  levelized cost of useful enrgy from cop residue in improved stove (Rs per MJ)
;
p_icrop=0.056
;
Parameters  p_lpg   levelized cost of useful enrgy from LPG (Rs per MJ)
;
p_lpg=1.5
;
Parameters  p_bgascook  levelized cost of useful enrgy from biogas cooking (Rs per MJ)
;
p_bgascook= 0.30
;
Parameters  tot_cookdem  total useful cooking energy demand (MJ per year) after considering all
efficiencies
;
tot_cookdem=  8280
;
Parameters  tot_ann_forest  total forest residue produced per year(kg per year)(annual household
firewood consumption with missing values and wood sold which was 200 is not included her)
;
tot_ann_forest= 1400
;
Parameters  tot_ann_LPGsupply  total possible LPG supply per year from government under PDS
scheme(MJ per year)  (14 multiply 12 multiply 45.56)
;
tot_ann_LPGsupply=  7654
;
Parameters  slurry_bgas_ratio  amount of slurry manure produced per MJ of useful energy by
biogas(kg per MJ) assuming 1 kg manure produce same slurry with same nutrients
;
slurry_bgas_ratio=  1.97
```

;
Parameters p_ker_n   price of kerosene_light_night (Rs per million lumenhours)
;
p_ker_n= 66318.88
;
Parameters p_sollight   price of solar LED light with battery at night (Rs per million lumenhours)
;
p_sollight= 89.78
;
Parameters p_n_solbatlight   price of solar LED light with battery at night (Rs per million lumenhours)
;
p_n_solbatlight= 190.95
;
Parameters p_n_gridlight price of grid with LED light at night   (Rs per million lumenhours)
;
p_n_gridlight= 34.78
;
Parameters p_n_gridbatlight price of grid with battery with LED light at night   (Rs per million lumenhours)
;
p_n_gridbatlight= 134.56
;
Parameters p_n_disgenlight price of diesel genset with LED light at night (Rs per million lumenhours)
;
p_n_disgenlight= 227.73
;
Parameters p_n_biogaslight price of biogas based light mantle (Rs per million lumenhours)
;
p_n_biogaslight= 1291.02
;
Parameters p_lpglight price of LPG based light mantle (Rs per million lumenhours)
;
p_lpglight= 7192.39
;
Parameters grid_light_current_sup_night current available grid supply based light at night (million lumenhours per year)
;
grid_light_current_sup_night= 4.24
;
Parameters grid_light_current_sup_day current available grid supply based light at day (million lumenhours per year)
;
grid_light_current_sup_day= 0
;
Parameters tot_light_req_night total lighting requirement at night (million lumenhours per year)
;
tot_light_req_night= 11.8
;
Parameters tot_light_req_day total lighting requirement at day (million lumenhours per year)

;
tot_light_req_day= 0
;
Parameters tot_pos_gridpower_day total possible grid power (non lighting)in day (MJ per year)
;
tot_pos_gridpower_day= 2486
;
Parameters tot_pos_gridpower_night total possible grid power (non lighting)in night (MJ per year)
;
tot_pos_gridpower_night= 1690
;
Parameters tot_power_req_day total power (non lighting) requirement at day including milling (MJ per year)
;
tot_power_req_day= 3883
;
Parameters tot_power_req_night total power (non lighting) requirement at night (MJ per year)
;
tot_power_req_night= 2831
;
Parameters tot_irrig_energ_req total irrigation energy requirement (MJ per year)
;
tot_irrig_energ_req= 2045
;
Parameters p_sol_power price of solar power (Rs per MJ)
;
p_sol_power= 1.89
;
Parameters p_solbat_power price of solar with battery power (Rs pr MJ)
;
p_solbat_power= 4.03
;
Parameters p_gridpower price of grid power (Rs per MJ)
;
p_gridpower= 0.734
;
Parameters p_gridbat_power price of grid with battery power (Rs per MJ)
;
p_gridbat_power= 2.84
;
Parameters p_disgen_power price of diesel genset power (Rs per MJ)
;
p_disgen_power= 4.80
;
Parameters p_bgas_power price of biogas based power (Rs per MJ)
;
p_bgas_power= 1.13
;
Parameters p_bgas_irrig price of biogas based irrigation energy (Rs per MJ)
;
p_bgas_irrig= 0.95

;
Parameters p_swp_irrig price of solar water pump based irrigation (Rs per MJ)
;
p_swp_irrig= 3.35
;
Parameters p_dis_irrig price of diesel engine based irrigation (Rs per MJ)
;
p_dis_irrig= 4.65
;
Parameters p_grid_irrig price of grid power based irrigation (Rs per MJ)
;
p_grid_irrig= 0.71
;
Parameters p_marketwater_irrig price of irrigation water from market (Rs per MJ). This is the price of water purchase from market
;
p_marketwater_irrig = 2.7
;
Parameters hdamage_tdung health damage cost per useful energy from traditional dung (Rs per MJ)
;
hdamage_tdung= 1.96
;
Parameters hdamage_idung health damage cost per useful energy from improved dung (Rs per MJ)
;
hdamage_idung= 1.17
;
Parameters hdamage_twood health damage cost per useful energy from traditional wood (Rs per MJ)
;
hdamage_twood= 0.38
;
Parameters hdamage_iwood health damage cost per useful energy from improved wood (Rs per MJ)
;
hdamage_iwood= 0.22
;
Parameters hdamage_tcrop health damage cost per useful energy from traditional crop res (Rs per MJ)
;
hdamage_tcrop= 0.64
;
Parameters hdamage_icrop health damage cost per useful energy from improved crop res (Rs per MJ)
;
hdamage_icrop= 0.37
;
Parameters hdamage_lpg health damage cost per useful energy from lpg (Rs per MJ)
;
hdamage_lpg= 0.020

;
Parameters hdamage_bgas health damage cost per useful energy from biogas (Rs per MJ)
;
hdamage_bgas= 0.05
;
Parameters hdamage_ker health damage cost from kerosene light (Rs per million lumenhours)
;
hdamage_ker= 1138.54
;
Parameters hdamage_sollight health damage cost from solar LED based lighting (Rs per million lumenhours)
;
hdamage_sollight= 0
;
Parameters hdamage_solbatlight health damage cost from lighting based on solar battery with LED (Rs per million lumenhours)
;
hdamage_solbatlight= 0
;
Parameters hdamage_gridlight health damage cost from grid based incandescent lighting (Rs per million lumenhours)
;
hdamage_gridlight= 0
;
Parameters hdamage_gridbatlight health damage cost from lighting based on grid with battery (Rs per million lumenhours)
;
hdamage_gridbatlight= 0
;
Parameters hdamage_disgenlight health damage cost from diesel genset based lighting (Rs per million lumenhours)
;
hdamage_disgenlight= 3.21
;
Parameters hdamage_bgaslight health damage cost from biogas mantle based lighting (Rs per million lumenhours)
;
hdamage_bgaslight= 209.15
;
Parameters hdamage_LPGlight health damage cost from LPG mantle lighting (Rs per million lumenhours)
;
hdamage_LPGlight= 99.06
;
Parameters hdamage_sol health damage cost per useful energy from solar power without battery (Rs per MJ)
;
hdamage_sol= 0
;
Parameters hdamage_solbat health damage cost per useful energy from solar power with battery (Rs per MJ)

;
hdamage_solbat= 0
;
Parameters hdamage_grid health damage cost per useful energy from grid power (Rs per MJ)
;
hdamage_grid= 0
;
Parameters hdamage_gridbat health damage cost per useful energy from grid power with battery (Rs per MJ)
;
hdamage_gridbat= 0
;
Parameters hdamage_disgen health damage cost per useful energy from diesel genset (Rs per MJ)
;
hdamage_disgen= 0.067
;
Parameters hdamage_bgaspower health damage cost per useful energy from biogas based power (Rs per MJ)
;
hdamage_bgaspower= 0.0097
;
Parameters pric_enercook_mg price of cooking energy per MJ from mini grid (Rs per MJ)
;
pric_enercook_mg = 1.17
;
Parameters pric_dlight_mg price of day light per million lumen hours from mini grid (42 Rs per MJ)
;
pric_dlight_mg = 77.8
;
Parameters pric_nlight_mg price of night light per million lumen hours from mini grid (50 Rs per MJ)
;
pric_nlight_mg = 136
;
Parameters pric_dpower_mg price of day power per MJ from mini grid (1.25 Rs per MJ)
;
pric_dpower_mg = 1.58
;
Parameters pric_npower_mg price of night power per MJ from mini grid (0.8 Rs per MJ)
;
pric_npower_mg = 2.23
;
Parameters pric_irrig_mg price of irrigation energy per MJ from mini grid (Rs per MJ)
;
pric_irrig_mg = 0.82
;
Parameters p_fund yearly maximum budget of household (150000 Rs per year)
;
p_fund = 150000
;

Parameters male_maxofffarm Yearly max Non-agricultural work opportunities for hh male (300 days per year)
;
male_maxofffarm = 358
;
Parameters female_maxofffarm Yearly max Non-agricultural work opportunities for hh female (days per year)
;
female_maxofffarm = 14
;
Parameters child_maxofffarm Yearly max Non-agricultural work opportunities for hh male (days per year)
;
child_maxofffarm = 2
;
Parameters p_arealimit Maximum land available for agriculture (acres)
;
p_arealimit= 4
;
Parameters p_lbrHH_male Total Annual male labor in the hh (days per year)
;
p_lbrHH_male = 531
;
Parameters p_lbrHH_female Total Annual female labor in the hh (days per year 317)
;
p_lbrHH_female = 246
;
Parameters p_lbrHH_child Total Annual child labor in the hh (days per year)
;
p_lbrHH_child = 80
;
Parameters p_labrice Total labor per acre required for rice cultivation (days per acre) here all labor (female male or child) converted into male labor
;
p_labrice = 42
;
Parameters p_labwheat Total labor per acre required for wheat cultivation (days per acre) here all labor (female male or child) converted into male labor
;
p_labwheat = 18.5
;
Parameters p_labsugar Total labor per acre required for sugarcane cultivation (days per acre)here all labor (female male or child) converted into male labor
;
p_labsugar = 50
;
Parameters p_labmustard Total labor per acre required for mustard cultivation (days per acre) here all labor (female male or child) converted into male labor
;
p_labmustard = 25.2
;

```
Parameters  p_labpotato Total labor per acre required for potato cultivation  (days per acre) here all labor (female male or child) converted into male labor
;
p_labpotato =  40.5
;
Parameters  p_labcon_rice_male Labor productivity conversion for male for rice compared to male (1)
;
p_labcon_rice_male =  1
;
Parameters  p_labcon_rice_female Labor productivity conversion for female for rice compared to male (1)
;
p_labcon_rice_female=  1.15
;
Parameters  p_labcon_rice_child Labor productivity conversion for child for rice compared to male (1)
;
p_labcon_rice_child =  0.5
;
Parameters  p_labcon_wheat_male Labor productivity conversion for male for wheat compared to male (1)
;
p_labcon_wheat_male =  1
;
Parameters  p_labcon_wheat_female Labor productivity conversion for female for wheat compared to male (1)
;
p_labcon_wheat_female =  0.8
;
Parameters  p_labcon_wheat_child Labor productivity conversion for child for wheat  compared to male (1)
;
p_labcon_wheat_child =  0.5
;

Parameters  p_labcon_sugar_male   Labor productivity conversion for male for sugar
;
p_labcon_sugar_male =  1
;
Parameters  p_labcon_sugar_female Labor productivity conversion for female for sugar
;
p_labcon_sugar_female =  0.66
;
Parameters  p_labcon_sugar_child   Labor productivity conversion for child for sugar
;
p_labcon_sugar_child =  0.33
;
Parameters  p_labcon_mustard_male Labor productivity conversion for male for mustard
;
p_labcon_mustard_male =  1
```

;
Parameters p_labcon_mustard_female   Labor productivity conversion for female for mustard
;
p_labcon_mustard_female = 0.8
;
Parameters p_labcon_mustard_child Labor productivity conversion for child for mustard
;
p_labcon_mustard_child = 0.5
;
Parameters p_labcon_potato_male Labor productivity conversion for male for potato
;
p_labcon_potato_male = 1
;
Parameters p_labcon_potato_female   Labor productivity conversion for female for potato
;
p_labcon_potato_female = 1.15
;
Parameters p_labcon_potato_child Labor productivity conversion for child for potato (as children is used a lot here so i have made it 0.7 instead of 0.5)
;
p_labcon_potato_child = 0.7
;
Parameters p_labrliv_cow Labor required per cow (all labor converted into male 124) days per head
;
p_labrliv_cow = 91
;
Parameters p_lablivcon_male_cow Labor productivity conversion for male for cow compared to male (1)
;
p_lablivcon_male_cow = 1
;
Parameters p_lablivcon_female_cow Labor productivity conversion for female for cow compared to male (1)
;
p_lablivcon_female_cow = 1
;
Parameters p_lablivcon_child_cow Labor productivity conversion for child for cow compared to male (1)
;
p_lablivcon_child_cow = 0.5
;
Parameters p_live_cow Initial number of cows in hh (numbers)
;
p_live_cow = 1
;
Parameters p_labrliv_buf Labor required per buffalo (all labor converted into male 210) days per head
;
p_labrliv_buf = 91
;

Parameters p_lablivcon_male_buf Labor productivity conversion for male for buffalo compared to male (1)
;
p_lablivcon_male_buf = 1
;
Parameters p_lablivcon_female_buf Labor productivity conversion for female for buffalo compared to male (1)
;
p_lablivcon_female_buf = 1
;
Parameters p_lablivcon_child_buf Labor productivity conversion for child for buffalo compared to male (1)
;
p_lablivcon_child_buf = 0.5
;
Parameters p_live_buffalo Initial number of buffalos in hh
;
p_live_buffalo = 2
;

Parameters p_labenbp_rstraw Labor required for rice straw production (lab days per kg)
;
p_labenbp_rstraw = 0.003
;
Parameters p_labenbp_malecon_rstraw Labor productivity conversion for male for rice straw
;
p_labenbp_malecon_rstraw = 1
;
Parameters p_labenbp_femalecon_rstraw Labor productivity conversion for female for rice straw
;
p_labenbp_femalecon_rstraw = 0.7
;
Parameters p_labenbp_childcon_rstraw Labor productivity conversion for child for rice straw
;
p_labenbp_childcon_rstraw = 0.5
;
Parameters p_labenbp_sleaves Labor required for sugarcane leaves production (days per acre)
;
p_labenbp_sleaves = 0.003
;
Parameters p_labenbp_malecon_sleaves Labor productivity conversion for male for sugarcane leaves
;
p_labenbp_malecon_sleaves = 1
;
Parameters p_labenbp_femalecon_sleaves Labor productivity conversion for female for sugarcane leaves
;
p_labenbp_femalecon_sleaves = 0.7
;

Parameters p_labenbp_childcon_sleaves Labor productivity conversion for child for sugarcane leaves
;
p_labenbp_childcon_sleaves = 0.5
;
Parameters p_labenbp_mstraw Labor required for mustard straw production (days per kg)
;
p_labenbp_mstraw = 0.003
;
Parameters p_labenbp_malecon_mstraw Labor productivity conversion for male for mustard straw
;
p_labenbp_malecon_mstraw = 1
;
Parameters p_labenbp_femalecon_mstraw Labor productivity conversion for female for mustard straw
;
p_labenbp_femalecon_mstraw = 0.7
;
Parameters p_labenbp_childcon_mstraw   Labor productivity conversion for child for mustard straw
;
p_labenbp_childcon_mstraw = 0.5
;

Parameters p_laben_dungcake Male Labor required for dung cake production (male labor days per kg 0.026)
;
p_laben_dungcake = 0.021
;
Parameters p_lab_malecon_dungcake Labor productivity conversion for male for dung cake
;
p_lab_malecon_dungcake = 1
;
Parameters p_lab_femalecon_dungcake Labor productivity conversion for female for dung cake compared to males
;
p_lab_femalecon_dungcake = 0.7
;
Parameters p_lab_childcon_dungcake   Labor productivity conversion for child for dung cake compared to child
;
p_lab_childcon_dungcake = 0.5
;
Parameters p_laben_bgas Labor required for biogas production (days per m3 0.030)
;
p_laben_bgas = 0.020
;
Parameters p_lab_malecon_bgas Labor productivity conversion for male for biogas
;
p_lab_malecon_bgas = 1
;
Parameters p_lab_femalecon_bgas Labor productivity conversion for female for biogas

```
;
p_lab_femalecon_bgas =  1
;
Parameters  p_lab_childcon_bgas   Labor productivity conversion for child for biogas
;
p_lab_childcon_bgas =  0.5
;
Parameters  p_labwood  Labor required for wood collection for energy  (days per kg)
;
p_labwood =  0.0058
;
Parameters  p_lab_malecon_wood  Labor productivity conversion for male for wood
;
p_lab_malecon_wood =  1
;
Parameters  p_lab_femalecon_wood  Labor productivity conversion for female for wood
;
p_lab_femalecon_wood =  0.7
;
Parameters  p_lab_childcon_wood   Labor productivity conversion for child for wood
;
p_lab_childcon_wood =  0.5
;
Parameters  p_yldcrop_wheat   Yield per acre of wheat crop (Kgs per acre)
;
p_yldcrop_wheat =  1514
;
Parameters  p_concrp_wheat   Per year consumption of wheat of hh (Kgs per year)
;
p_concrp_wheat =  918
;
Parameters  p_fedcrp_wheat_buf   Per year consumption of wheat for buffalo feed (Kgs per year)
;
p_fedcrp_wheat_buf =  574
;
Parameters  p_fedcrp_wheat_cow   Per year consumption of wheat for cow feed (Kgs per year)
;
p_fedcrp_wheat_cow =  227
;
Parameters  p_yldcrop_rice   Yield per acre of rice crop (Kgs per acre)
;
p_yldcrop_rice =  1307
;
Parameters  p_concrp_rice   Per year consumption of rice per hh (Kgs per year)
;
p_concrp_rice =  460
;
Parameters  p_fedcrp_rice_buf   Per year consumption of rice for buffalo feed (Kgs per year)
;
p_fedcrp_rice_buf =  0
;
```

```
Parameters  p_fedcrp_rice_cow   Per year consumption of rice for cow feed (Kgs per year)
;
p_fedcrp_rice_cow =  0
;
Parameters  p_yldcrop_sugar   Yield per acre of sugar crop (Kgs per acre)
;
p_yldcrop_sugar =  24226
;
Parameters  p_concrp_sugar   Per year consumption of sugar (Kgs per year 297)
;
p_concrp_sugar =  297
;
Parameters  p_fedcrp_sugar_buf   Per year consumption of sugar for buffalo feed (Kgs per year)
;
p_fedcrp_sugar_buf =  0
;
Parameters  p_fedcrp_sugar_cow   Per year consumption of sugar for cow feed (Kgs per year)
;
p_fedcrp_sugar_cow =  0
;
Parameters  p_yldcrop_mustard   Yield per acre of mustard crop (Kgs per acre)
;
p_yldcrop_mustard =  380
;
Parameters  p_concrp_mustard   Per year consumption of mustard (Kgs per year)
;
p_concrp_mustard =  192
;
Parameters  p_fedcrp_mustard_buf   Per year consumption of mustard for buffalo feed (Kgs per
year)
;
p_fedcrp_mustard_buf =  0
;
Parameters  p_fedcrp_mustard_cow   Per year consumption of mustard for cow feed (Kgs per year)
;
p_fedcrp_mustard_cow =  0
;
Parameters  p_yldcrop_potato  Yield per acre of potato crop (Kgs per acre)
;
p_yldcrop_potato =  10524
;
Parameters  p_concrp_potato   Per year consumption of potato (Kgs per year)
;
p_concrp_potato =  400
;
Parameters  p_fedcrp_potato_buf   Per year consumption of potato for buffalo feed (Kgs per year)
;
p_fedcrp_potato_buf =  0
;
Parameters  p_fedcrp_potato_cow   Per year consumption of potato for cow feed (Kgs per year)
;
```

p_fedcrp_potato_cow = 0
;

Parameters p_bprcrop_rstraw Ratio of rice straw to rice production
;
p_bprcrop_rstraw = 1.5
;
Parameters p_fedcrp_rstraw_buf Per year consumption of rice straw for buffalo feed (Kgs per year)
;
p_fedcrp_rstraw_buf = 1040
;
Parameters p_fedcrp_rstraw_cow Per year consumption of rice straw for cow feed (Kgs per year)
;
p_fedcrp_rstraw_cow = 746
;
Parameters p_bprcrop_rhusk Ratio of rice husk to rice producton
;
p_bprcrop_rhusk = 0.2
;
Parameters p_fedcrp_rhusk_buf Per year consumption of rice husk for buffalo feed (Kgs per year)
;
p_fedcrp_rhusk_buf = 0
;
Parameters p_fedcrp_rhusk_cow Per year consumption of rice husk for cow feed (Kgs per year)
;
p_fedcrp_rhusk_cow = 0
;
Parameters p_bprcrop_wstraw Ratio of wheat straw to rice production
;
p_bprcrop_wstraw = 1.5
;
Parameters p_fedcrp_wstraw_buf Per year consumption of wheat straw for buffalo feed (Kgs per year)
;
p_fedcrp_wstraw_buf = 1040
;
Parameters p_fedcrp_wstraw_cow Per year consumption of wheat straw for cow feed (Kgs per year)
;
p_fedcrp_wstraw_cow = 746
;
Parameters p_bprcrop_stop Ratio of sugarcane top to sugarcane producton
;
p_bprcrop_stop = 0.1
;
Parameters p_fedcrp_stop_buf Per year consumption of sugarcane top for buffalo feed (Kgs per year)
;
p_fedcrp_stop_buf = 887
;

Parameters p_fedcrp_stop_cow   Per year consumption of sugarcane top for cow feed (Kgs per year)
;
p_fedcrp_stop_cow = 527
;
Parameters p_bprcrop_sleaves Ratio of sugarcane leaves to sugarcane production
;
p_bprcrop_sleaves = 0.04
;
Parameters p_fedcrp_sleaves_buf   Per year consumption of sugarcane leaves for buffalo feed (Kgs per year)
;
p_fedcrp_sleaves_buf = 0
;
Parameters p_fedcrp_sleaves_cow   Per year consumption of sugarcane leaves for cow feed (Kgs per year)
;
p_fedcrp_sleaves_cow = 0
;
Parameters p_bprcrop_mstraw Ratio of mustard straw to mustard production
;
p_bprcrop_mstraw = 1.8
;
Parameters p_fedcrp_mstraw_buf   Per year consumption of mustard straw for buffalo feed (Kgs per year)
;
p_fedcrp_mstraw_buf = 0
;
Parameters p_fedcrp_mstraw_cow   Per year consumption of mustard straw for cow feed (Kgs per year)
;
p_fedcrp_mstraw_cow = 0
;
Parameters p_bprcrop_mcake Ratio of mustard cake to mustard production
;
p_bprcrop_mcake = 0.65
;
Parameters p_fedcrp_mcake_buf Per year consumption of mustard cake for buffalo feed (Kgs per year)
;
p_fedcrp_mcake_buf = 224
;
Parameters p_fedcrp_mcake_cow   Per year consumption of mustard cake for cow feed (Kgs per year)
;
p_fedcrp_mcake_cow = 160
;
Parameters p_prodliv_milk_cow   Yearly Output of milk per cow (liters per cow)
;
p_prodliv_milk_cow = 1447
;

```
Parameters  p_prodliv_milk_buf   Yearly Output of milk per buffalo (liters per buffalo)
;
p_prodliv_milk_buf =  1573
;
Parameters  p_conliv_cow_milk   Yearly consumption of cow milk (liters per year)
;
p_conliv_cow_milk =  656
;
Parameters  p_conliv_buf_milk   Yearly consumption of buffalo milk (liters per year)
;
p_conliv_buf_milk =  656
;
Parameters  p_prodliv_manure_cow   Yearly Output of manure per cow (kgs per cow)
;
p_prodliv_manure_cow =  5360
;
Parameters  p_prodliv_manure_buf   Yearly Output of milk per buffalo (kgs per buffalo)
;
p_prodliv_manure_buf =  5805
;
Parameters  p_mnrcrp_wheat   Yearly manure requirement for wheat (Kgs per acre 1006)
;
p_mnrcrp_wheat = 1006
;
Parameters  p_mnrcrp_rice   Yearly manure requirement for Rice (Kgs per acre 2273)
;
p_mnrcrp_rice =  2273
;
Parameters  p_mnrcrp_sugar   Yearly manure requirement for sugarcane (Kgs per acre)
;
p_mnrcrp_sugar = 2543
;
Parameters  p_mnrcrp_mustard   Yearly manure requirement for Mustard (Kgs per acre)
;
p_mnrcrp_mustard =  310
;
Parameters  p_mnrcrp_potato   Yearly manure requirement for potato (Kgs per acre)
;
p_mnrcrp_potato =  7545
;
Parameters  p_irrigener_wheat   Irrigation Energy Requiremet of wheat per acre (MJ per acre)
;
p_irrigener_wheat =  1066
;
Parameters  p_irrigener_rice   Irrigation Energy Requiremet of rice per acre (MJ per acre)
;
p_irrigener_rice =  1607
;
Parameters  p_irrigener_sugar   Irrigation Energy Requiremet of sugar per acre (MJ per acre)
;
p_irrigener_sugar =  1866
```

;
Parameters p_irrigener_mustard   Irrigation Energy Requiremet of mustard per acre (MJ per acre)
;
p_irrigener_mustard = 442
;
Parameters p_irrigener_potato   Irrigation Energy Requiremet of potato per acre (MJ per acre)
;
p_irrigener_potato = 769
;

Parameters perc_woodtomg   Percentage of household wood given to mini grid by household 0.5
;
perc_woodtomg = 0.7
;
Parameters perc_dungtomg   Percentage of household dung given to mini grid by household
;
perc_dungtomg = 0.0
;
Parameters perc_rstrawtomg   Percentage of household rice straw given to mini grid by household
;
perc_rstrawtomg = 0.62
;
Parameters perc_crprestomg   Percentage of household crop residues given to mini grid by household
;
perc_crprestomg = 1
;
Parameters p_woodbuyprice   Buying Wood price per kg (Rs per kg)
;
p_woodbuyprice = 6
;
Parameters p_woodsaleprice   Selling Wood price per kg (Rs per kg)
;
p_woodsaleprice = 1.5
;

**** Declaring equations and constraints for the model***

Equations
obj,
budget,
con_budget,
con_offrm_male,
con_offrm_female,
con_offrm_child,
con_land_wheat,
con_land_rice,
con_land_sugar,
con_land_mustard,

con_land_potato,
con_land_winter,
con_land_summer,
con_laborHH_male,
con_laborHH_female,
con_laborHH_child,
con_labrice,
con_labwheat,
con_labsugar,
con_labmustard,
con_labpotato,
con_lablivcowbal,
con_cowbal,
con_lablivbufbal,
con_bufbal,
con_labenbp_rstraw,
con_labenbp_sleaves,
con_labenbp_mstraw,
con_laben_dungcake,
con_laben_bgas,
con_labenwood,
con_laboroffarm_male,
con_laboroffarm_female,
con_laboroffarm_child,
con_labagrifrmout_male,
con_labagrifrmout_female,
con_labagrifrmout_child,
con_cropbal_wheat,
con_cropbal_rice,
con_cropbal_sugar,
con_cropbal_mustard,
con_cropbal_potato,
con_balslcrp_wheat,
con_balslcrp_rice,
con_balslcrp_sugar,
con_balslcrp_mustard,
con_balslcrp_potato,
con_balbucrp_wheat,
con_balbucrp_rice,
con_balbucrp_sugar,
con_balbucrp_mustard,
con_balbucrp_potato,
con_bprbal_rstraw,
con_bprbal_rhusk,
con_bprbal_wstraw,

con_bprbal_stop,
con_bprbal_sleaves,
con_bprbal_must,
con_bprbal_mcake,
con_balslbp_rstraw,
con_balslbp_rhusk,
con_balslbp_wstraw,
con_balslbp_stop,
con_balslbp_mstraw,
con_balslbp_mcake,
con_balslbp_sleaves,
con_balbubp_rstraw,
con_balbubp_rhusk,
con_balbubp_wstraw,
con_balbubp_stop,
con_balbubp_sleaves,
con_balbubp_sleaves_max,
con_balbubp_mstraw,
con_balbubp_mcake,
con_livsl_cow,
con_livsl_buf,
con_livbu_cow,
con_livbu_buf,
con_baliv_milk,
con_baliv_manure,
con_balivsl_milk,
con_balivsl_bufmilk,
con_balivsl_cowmilk,
con_balivsl_manure,
con_balivbu_milk,
con_balivbu_manure,
con_allcrop_manure,
con_wheat_manure,
con_rice_manure,
con_sugar_manure,
con_mustard_manure,
con_potato_manure,
con_dcake,
con_bgas,
con_cropres_energy,
con_dung,
con_slurry,
con_wood,
con_cropres,
con_totcookdem,

```
con_grid_light_night,
con_grid_light_day,
con_tot_nightlight,
con_tot_daylight,
con_grid_power_day,
con_grid_power_night,
con_tot_daypower,
con_tot_nightpower,
con_tot_irrigation_energydemand,
con_HHlabmale_energy,
con_tot_ener_expense,
con_healthcost,
con_co2emis,
con_wood_balance,
con_wood_salebalance,
con_wood_buybalance,
con_cookenergy_price,
*con_hhrevenue,
con_daypower_price,
con_nightpower_price,
con_nightlight_price,
con_irrig_ener_price;
```

**** Defining Equations of the model***

**** Objective function of the household**: Maximization of the annual household income (discounted annual net present value over 15 years period)*

```
obj..
    v_obj =E=
rice_price * v_rice_sale  + wheat_price * v_wheat_sale +  sugar_price * v_sugar_sale +
mustard_price * v_mustard_sale  +  potato_price * v_potato_sale  + rhusk_price * v_rhusk_sale +
rstraw_price * v_rstraw_sale + wstraw_price* v_wstraw_sale +  stop_price * v_stop_sale
+ sleaves_price * v_sleaves_sale  + mstraw_price * v_mstraw_sale + mcake_price * v_mcake_sale   +
v_cowmilk_sale * cowmilk_price + v_cowmanure_sale * 0.4
  + v_bufmilk_sale * bufmilk_price + v_bufmanure_sale * 0.4   + cow_price * v_cow_headsale +
buf_price * v_buf_headsale  + jobwag_male * v_nonagrilab_male + jobwag_female *
v_nonagrilab_female + jobwag_child * v_nonagrilab_child   + farmwage_male * v_farmlabout_male
+  farmwage_female * v_farmlabout_female + farmwage_child * v_farmlabout_child
+(p_bprcrop_rstraw * p_yldcrop_rice  *  v_rice_area)*perc_rstrawtomg* rstraw_price +
(p_bprcrop_rhusk * p_yldcrop_rice  *  v_rice_area)* perc_crprestomg * rhusk_price
 + (p_bprcrop_sleaves * p_yldcrop_sugar  *  v_sugar_area)*perc_crprestomg * sleaves_price
+ tot_ann_forest*perc_woodtomg* p_woodbuyprice   + (p_prodliv_manure_cow  *
v_live_cow)*perc_dungtomg*cowmanure_price + (p_prodliv_manure_buf  * v_live_buffalo)*
```

perc_dungtomg * bufmanure_price + v_wood_sale * p_woodsaleprice - farmwage_male * v_farmlabin_male - farmwage_female * v_farmlabin_female - farmwage_child * v_farmlabin_child - rice_costinp * v_rice_area - wheat_costinp * v_wheat_area - sugar_costinp * v_sugar_area - mustard_costinp * v_mustard_area - potato_costinp * v_potato_area - v_rice_buy * rice_price - v_wheat_buy * wheat_price - v_sugar_buy * sugar_price - v_mustard_buy * mustard_price - v_potato_buy * potato_price - v_rhusk_buy * rhusk_price - v_rstraw_buy * rstraw_price - v_wstraw_buy * wstraw_price - v_stop_buy* stop_price - v_sleaves_buy * sleaves_price - v_mstraw_buy * mstraw_price - v_mcake_buy * mcake_price - v_cowmilk_buy * cowmilk_price - v_cowmanure_buy * 0.6 - v_bufmilk_buy * bufmilk_price - v_bufmanure_buy * 0.6 - cow_price * v_cow_headbuy - buf_price * v_buf_headbuy - v_wood_buy * p_woodbuyprice
-
(t_dung*p_tdung + i_dung*p_idung + t_wood*p_twood + i_wood*p_iwood + t_crop*p_tcrop + i_crop*p_icrop + lpg*p_lpg + bgas_cook*p_bgascook
+ n_ker_light*p_ker_n + n_solbat_light*p_n_solbatlight + n_grid_light*p_n_gridlight + n_gridbat_light*p_n_gridbatlight + n_disgen_light*p_n_disgenlight + n_biogas_light*p_n_biogaslight + n_lpg_light*p_lpglight + d_ker_light*p_ker_n + d_solbat_light*p_n_solbatlight + p_sollight*d_sol_light + d_grid_light*p_n_gridlight
+ d_gridbat_light*p_n_gridbatlight + d_disgen_light*p_n_disgenlight + d_biogas_light*p_n_biogaslight + d_lpg_light*p_lpglight
+ d_sol_power*p_sol_power + d_solbat_power*p_solbat_power + d_grid_power*p_gridpower + d_gridbat_power*p_gridbat_power
+ d_disgen_power*p_disgen_power + d_bgas_power* p_bgas_power
+ n_solbat_power*p_solbat_power + n_grid_power*p_gridpower
+ n_gridbat_power*p_gridbat_power + n_disgen_power*p_disgen_power + n_bgas_power* p_bgas_power + swp_irrig*p_swp_irrig + dis_irrig*p_dis_irrig + grid_irrig*p_grid_irrig + bgas_irrig* p_bgas_irrig + marketwater_irrig*p_marketwater_irrig + v_enercook_mg*pric_enercook_mg + v_dlight_mg*pric_dlight_mg + v_nlight_mg*pric_nlight_mg + v_dpower_mg*pric_dpower_mg
+ v_npower_mg*pric_npower_mg + v_irrig_mg*pric_irrig_mg) ;

**** budget constraint of the household***

budget..
v_budg =G=
farmwage_male * v_farmlabin_male + farmwage_female * v_farmlabin_female + farmwage_child * v_farmlabin_child + rice_costinp * v_rice_area + wheat_costinp * v_wheat_area + sugar_costinp * v_sugar_area + mustard_costinp * v_mustard_area + potato_costinp * v_potato_area + v_rice_buy * rice_price + v_wheat_buy * wheat_price + v_sugar_buy * sugar_price + v_mustard_buy * mustard_price + v_potato_buy * potato_price
+ v_rhusk_buy * rhusk_price + v_rstraw_buy * rstraw_price + v_wstraw_buy * wstraw_price
+ v_stop_buy* stop_price + v_sleaves_buy * sleaves_price + v_mstraw_buy * mstraw_price + v_mcake_buy * mcake_price + v_cowmilk_buy * cowmilk_price + v_cowmanure_buy * 0.6
+ v_bufmilk_buy * bufmilk_price + v_bufmanure_buy * 0.6 + cow_price * v_cow_headbuy + buf_price * v_buf_headbuy + v_wood_buy * p_woodbuyprice + t_dung*p_tdung + i_dung*p_idung
+ t_wood*p_twood + i_wood*p_iwood + t_crop*p_tcrop + i_crop*p_icrop + lpg*p_lpg + bgas_cook*p_bgascook + n_ker_light*p_ker_n + n_solbat_light*p_n_solbatlight +

n_grid_light*p_n_gridlight + n_gridbat_light*p_n_gridbatlight + n_disgen_light*p_n_disgenlight + n_biogas_light*p_n_biogaslight + n_lpg_light*p_lpglight + d_ker_light*p_ker_n + d_solbat_light*p_n_solbatlight + p_sollight*d_sol_light + d_grid_light*p_n_gridlight + d_gridbat_light*p_n_gridbatlight + d_disgen_light*p_n_disgenlight + d_biogas_light*p_n_biogaslight + d_lpg_light*p_lpglight + d_sol_power*p_sol_power + d_solbat_power*p_solbat_power + d_grid_power*p_gridpower + d_gridbat_power*p_gridbat_power + d_disgen_power*p_disgen_power + d_bgas_power* p_bgas_power + n_solbat_power*p_solbat_power + n_grid_power*p_gridpower + n_gridbat_power*p_gridbat_power + n_disgen_power*p_disgen_power + n_bgas_power* p_bgas_power + swp_irrig*p_swp_irrig + dis_irrig*p_dis_irrig + grid_irrig*p_grid_irrig + bgas_irrig* p_bgas_irrig + marketwater_irrig*p_marketwater_irrig + v_enercook_mg*pric_enercook_mg + v_dlight_mg*pric_dlight_mg + v_nlight_mg*pric_nlight_mg + v_dpower_mg*pric_dpower_mg + v_npower_mg*pric_npower_mg + v_irrig_mg*pric_irrig_mg ;

****   Annual Budget available for household expenditures (in Rs)***

con_budget.. v_budg =E= p_fund;

****   Constraint on land availability for farming (acres)***

con_land_wheat.. v_wheat_area =L= p_arealimit;
con_land_rice.. v_rice_area =L= p_arealimit;
con_land_sugar.. v_sugar_area =L= p_arealimit;
con_land_mustard.. v_mustard_area =L= p_arealimit;
con_land_potato.. v_potato_area =L= p_arealimit;
con_land_winter.. v_wheat_area + v_potato_area + v_mustard_area + v_sugar_area =L= p_arealimit;
con_land_summer.. v_rice_area + v_sugar_area =L= p_arealimit;

****   Constraint on annual labor for household by gender and age (in days)***

con_laborHH_male..
v_labrice_male + v_labwheat_male + v_labsugar_male + v_labmustard_male + v_labpotato_male + v_nonagrilab_male + v_labliv_male_cow + v_labliv_male_buffalo + v_labbp_male_rstraw + v_labbp_male_sleaves + v_labbp_male_mstraw + v_labdngcake_male + v_labbgas_male + v_labenwood_male + v_farmlabout_male =L= p_lbrHH_male;

con_laborHH_female..
v_labrice_female + v_labwheat_female + v_labsugar_female + v_labmustard_female + v_labpotato_female + v_nonagrilab_female + v_labliv_female_cow + v_labliv_female_buffalo + v_labbp_female_rstraw + v_labbp_female_sleaves + v_labbp_female_mstraw + v_labdngcake_female + v_labbgas_female + v_labenwood_female + v_farmlabout_female =L= p_lbrHH_female;

con_laborHH_child..
v_labrice_child + v_labwheat_child + v_labsugar_child + v_labmustard_child + v_labpotato_child

+ v_nonagrilab_child + v_labliv_child_cow + v_labliv_child_buffalo + v_labbp_child_rstraw + v_labbp_child_sleaves + v_labbp_child_mstraw + v_labdngcake_child + v_labbgas_child + v_labenwood_child + v_farmlabout_child =L= p_lbrHH_child;

Labor balance for farm agriculture by gender and age (in days)

con_labrice.. p_labrice * v_rice_area =E= p_labcon_rice_male * v_labrice_male + p_labcon_rice_female * v_labrice_female + p_labcon_rice_child * v_labrice_child;

con_labwheat.. p_labwheat * v_wheat_area =E= p_labcon_wheat_male * v_labwheat_male + p_labcon_wheat_female * v_labwheat_female + p_labcon_wheat_child * v_labwheat_child;

con_labsugar.. p_labsugar * v_sugar_area =E= p_labcon_sugar_male * v_labsugar_male + p_labcon_sugar_female * v_labsugar_female + p_labcon_sugar_child * v_labsugar_child;

con_labmustard.. p_labmustard * v_mustard_area =E= p_labcon_mustard_male * v_labmustard_male + p_labcon_mustard_female * v_labmustard_female + p_labcon_mustard_child * v_labmustard_child;

con_labpotato.. p_labpotato * v_potato_area =E= p_labcon_potato_male * v_labpotato_male + p_labcon_potato_female * v_labpotato_female + p_labcon_potato_child * v_labpotato_child;

Labor balance for livestock rearing by gender and age (in days)

con_lablivcowbal..
p_labrliv_cow * v_live_cow =E= p_lablivcon_male_cow * v_labliv_male_cow + p_lablivcon_female_cow * v_labliv_female_cow + p_lablivcon_child_cow * v_labliv_child_cow;

con_cowbal.. v_live_cow =E= p_live_cow + v_cow_headbuy - v_cow_headsale;

con_lablivbufbal..
p_labrliv_buf * v_live_buffalo =E= p_lablivcon_male_buf * v_labliv_male_buffalo + p_lablivcon_female_buf * v_labliv_female_buffalo + p_lablivcon_child_buf * v_labliv_child_buffalo;

con_bufbal.. v_live_buffalo =E= p_live_buffalo + v_buf_headbuy - v_buf_headsale;

Labor balance for crop residue production by gender and age (in days)

con_labenbp_rstraw.. p_labenbp_rstraw * (p_bprcrop_rstraw * p_yldcrop_rice * v_rice_area) =E= p_labenbp_malecon_rstraw * v_labbp_male_rstraw + p_labenbp_femalecon_rstraw * v_labbp_female_rstraw + p_labenbp_childcon_rstraw * v_labbp_child_rstraw;

con_labenbp_sleaves.. p_labenbp_sleaves * (p_bprcrop_sleaves * p_yldcrop_sugar * v_sugar_area) =E= p_labenbp_malecon_sleaves * v_labbp_male_sleaves +

p_labenbp_femalecon_sleaves * v_labbp_female_sleaves + p_labenbp_childcon_sleaves * v_labbp_child_sleaves;

con_labenbp_mstraw..   p_labenbp_mstraw * (p_bprcrop_mstraw * p_yldcrop_mustard * v_mustard_area) =E= p_labenbp_malecon_mstraw * v_labbp_male_mstraw + p_labenbp_femalecon_mstraw * v_labbp_female_mstraw + p_labenbp_childcon_mstraw * v_labbp_child_mstraw;

****   Labor balance for dung based and wood based bioenergy production by gender and age (in days)***

con_laben_dungcake..
p_laben_dungcake * v_dungcake =E=   p_lab_malecon_dungcake * v_labdngcake_male +
p_lab_femalecon_dungcake * v_labdngcake_female +
p_lab_childcon_dungcake * v_labdngcake_child;

con_laben_bgas..
p_laben_bgas * v_bgas =E=   p_lab_malecon_bgas * v_labbgas_male + p_lab_femalecon_bgas * v_labbgas_female + p_lab_childcon_bgas * v_labbgas_child;

con_labenwood..
p_labwood* ((t_wood/0.18)/19.71 + (i_wood/0.3)/19.71 + tot_ann_forest*perc_woodtomg)   =E=
p_lab_malecon_wood * v_labenwood_male   + p_lab_femalecon_wood * v_labenwood_female +
p_lab_childcon_wood * v_labenwood_child;

****   Non-agricultural work opportunities for households by gender and age (days)***

con_offrm_male..
    v_nonagrilab_male =L= male_maxofffarm;

con_offrm_female..
    v_nonagrilab_female =L= female_maxofffarm;

con_offrm_child..
    v_nonagrilab_child =L= child_maxofffarm;

****   Constraints on non-agricultural household labor by gender and age (in days)***

con_laboroffarm_male..
    v_nonagrilab_male =L= p_lbrHH_male;

con_laboroffarm_female..
    v_nonagrilab_female =L= p_lbrHH_female;

con_laboroffarm_child..

```
            v_nonagrilab_child =L= p_lbrHH_child;
```

***   Constraints on off-farm agricultural household labor by gender and age (in days)***

```
*       Labor hired out for agricultural purposes at another farm
con_labagrifrmout_male..     v_farmlabout_male =E= 0;

*       Labor hired out for agricultural purposes at another farm
con_labagrifrmout_female..     v_farmlabout_female =E= 0;

*       Labor hired out for agricultural purposes at another farm
con_labagrifrmout_child..     v_farmlabout_child =E= 0;
```

**** Balance of crop main products***

```
con_cropbal_wheat..   p_yldcrop_wheat *  v_wheat_area  =E=  v_wheat_sale + p_concrp_wheat
+ p_fedcrp_wheat_buf * v_live_buffalo + p_fedcrp_wheat_cow * v_live_cow   - v_wheat_buy
;
con_cropbal_rice..   p_yldcrop_rice *  v_rice_area  =E=  v_rice_sale +  p_concrp_rice
                 + p_fedcrp_rice_buf * v_live_buffalo + p_fedcrp_rice_cow * v_live_cow   - v_rice_buy
;
con_cropbal_sugar..   p_yldcrop_sugar *  v_sugar_area  =E=  v_sugar_sale +  p_concrp_sugar
+ p_fedcrp_sugar_buf * v_live_buffalo + p_fedcrp_sugar_cow * v_live_cow   - v_sugar_buy
;
con_cropbal_mustard..   p_yldcrop_mustard *  v_mustard_area   =E=  v_mustard_sale +
p_concrp_mustard   + p_fedcrp_mustard_buf * v_live_buffalo + p_fedcrp_mustard_cow *
v_live_cow   - v_mustard_buy
;
con_cropbal_potato..   p_yldcrop_potato *  v_potato_area  =E=  v_potato_sale +  p_concrp_potato
+ p_fedcrp_potato_buf * v_live_buffalo + p_fedcrp_potato_cow * v_live_cow   - v_potato_buy
;
con_balslcrp_wheat..
  p_yldcrop_wheat *  v_wheat_area  =G= v_wheat_sale;
con_balslcrp_rice..
               p_yldcrop_rice *  v_rice_area  =G= v_rice_sale;
con_balslcrp_sugar..
               p_yldcrop_sugar *  v_sugar_area  =G= v_sugar_sale;
con_balslcrp_mustard..
               p_yldcrop_mustard *  v_mustard_area  =G= v_mustard_sale;
con_balslcrp_potato..
               p_yldcrop_potato *  v_potato_area  =G= v_potato_sale;
con_balbucrp_wheat..      v_wheat_buy  =E=  v_wheat_sale + p_concrp_wheat +
p_fedcrp_wheat_buf * v_live_buffalo    + p_fedcrp_wheat_cow * v_live_cow - p_yldcrop_wheat *
v_wheat_area;
```

con_balbucrp_rice..   v_rice_buy =E= v_rice_sale + p_concrp_rice + p_fedcrp_rice_buf * v_live_buffalo   + p_fedcrp_rice_cow * v_live_cow - p_yldcrop_rice * v_rice_area
;
con_balbucrp_sugar..   v_sugar_buy =E= v_sugar_sale + p_concrp_sugar + p_fedcrp_sugar_buf * v_live_buffalo + p_fedcrp_sugar_cow * v_live_cow - p_yldcrop_sugar * v_sugar_area
;
con_balbucrp_mustard..   v_mustard_buy =E= v_mustard_sale + p_concrp_mustard + p_fedcrp_mustard_buf * v_live_buffalo + p_fedcrp_mustard_cow * v_live_cow - p_yldcrop_mustard * v_mustard_area
;
con_balbucrp_potato..   v_potato_buy =E= v_potato_sale + p_concrp_potato + p_fedcrp_potato_buf * v_live_buffalo + p_fedcrp_potato_cow * v_live_cow - p_yldcrop_potato * v_potato_area
;

**** Balance of crop byproducts***
con_bprbal_rstraw..
(p_bprcrop_rstraw * p_yldcrop_rice * v_rice_area)*(1-perc_rstrawtomg) =E= v_rstraw_sale + p_fedcrp_rstraw_buf * v_live_buffalo + p_fedcrp_rstraw_cow * v_live_cow + v_enbp_rstraw - v_rstraw_buy ;

con_bprbal_rhusk..
p_bprcrop_rhusk * p_yldcrop_rice * v_rice_area *perc_crprestomg =E= v_rhusk_mg;

* this rice husk can only go in mini grid
con_bprbal_wstraw..
p_bprcrop_wstraw * p_yldcrop_wheat * v_wheat_area =E= v_wstraw_sale + p_fedcrp_wstraw_buf * v_live_buffalo + p_fedcrp_rstraw_cow * v_live_cow
+ v_enbp_wstraw - v_wstraw_buy ;
con_bprbal_stop..
p_bprcrop_stop * p_yldcrop_sugar * v_sugar_area *perc_crprestomg =E= v_stop_sale + p_fedcrp_stop_buf * v_live_buffalo + p_fedcrp_stop_cow * v_live_cow + v_enbp_stop - v_stop_buy
;
con_bprbal_sleaves..
p_bprcrop_sleaves * p_yldcrop_sugar * v_sugar_area =E= v_sleaves_mg;

con_bprbal_must..
p_bprcrop_mstraw * p_yldcrop_mustard * v_mustard_area =E= v_mstraw_sale + p_fedcrp_mstraw_buf * v_live_buffalo + p_fedcrp_mstraw_cow * v_live_cow + v_enbp_mstraw - v_mstraw_buy;

con_bprbal_mcake..
p_bprcrop_mcake * p_yldcrop_mustard * v_mustard_area =E= v_mcake_sale + p_fedcrp_mcake_buf * v_live_buffalo + p_fedcrp_mcake_cow * v_live_cow + v_enbp_mcake - v_mcake_buy;

```
con_balslbp_rstraw..     (p_bprcrop_rstraw * p_yldcrop_rice  *  v_rice_area)* (1-perc_rstrawtomg)
                =G=     v_rstraw_sale;

con_balslbp_rhusk..     (p_bprcrop_rhusk * p_yldcrop_rice  *  v_rice_area)*(1-perc_crprestomg)
                =E=     v_rhusk_sale;

con_balslbp_wstraw..     p_bprcrop_wstraw * p_yldcrop_wheat  *  v_wheat_area
                =G=     v_wstraw_sale;

con_balslbp_stop..     p_bprcrop_stop * p_yldcrop_sugar  *  v_sugar_area
                =G=     v_stop_sale;

con_balslbp_sleaves..     (p_bprcrop_sleaves * p_yldcrop_sugar  *  v_sugar_area)*(1-
perc_crprestomg)
                =E=     v_sleaves_sale;

con_balslbp_mstraw..     p_bprcrop_mstraw * p_yldcrop_mustard  *  v_mustard_area
                =G=     v_mstraw_sale;

con_balslbp_mcake..     p_bprcrop_mcake * p_yldcrop_mustard  *  v_mustard_area
                =G=     v_mcake_sale;

con_balbubp_rstraw..
  v_rstraw_buy =E=   p_fedcrp_rstraw_cow  * v_live_cow + p_fedcrp_rstraw_buf  * v_live_buffalo
  + v_enbp_rstraw + v_rstraw_sale   - (p_bprcrop_rstraw  * p_yldcrop_rice      * v_rice_area)*(1-
perc_rstrawtomg);

con_balbubp_rhusk..
v_rhusk_buy =E=   p_fedcrp_rhusk_cow  * v_live_cow + p_fedcrp_rhusk_buf  * v_live_buffalo
+ v_enbp_rhusk - (p_bprcrop_rhusk  * p_yldcrop_rice      * v_rice_area)*(1-perc_crprestomg);

con_balbubp_wstraw..
v_wstraw_buy =E=   p_fedcrp_wstraw_cow  * v_live_cow + p_fedcrp_wstraw_buf  * v_live_buffalo
+ v_enbp_wstraw + v_wstraw_sale   - p_bprcrop_wstraw  * p_yldcrop_wheat      * v_wheat_area;

con_balbubp_stop..
  v_stop_buy =E=  p_fedcrp_stop_cow  * v_live_cow + p_fedcrp_stop_buf  * v_live_buffalo
  + v_enbp_stop + v_stop_sale   - p_bprcrop_stop  * p_yldcrop_sugar      * v_sugar_area;

con_balbubp_sleaves..
   v_sleaves_buy =E=   p_fedcrp_sleaves_cow  * v_live_cow + p_fedcrp_sleaves_buf  * v_live_buffalo
   + v_enbp_sleaves - (p_bprcrop_sleaves  * p_yldcrop_sugar      * v_sugar_area )*(1-
perc_crprestomg);
```

```
con_balbubp_sleaves_max..
                  v_sleaves_buy =E= 0;
con_balbubp_mstraw..
  v_mstraw_buy =E=  p_fedcrp_mstraw_cow  * v_live_cow + p_fedcrp_mstraw_buf  * v_live_buffalo
   + v_enbp_mstraw + v_mstraw_sale   - p_bprcrop_mstraw  * p_yldcrop_mustard *
v_mustard_area;

con_balbubp_mcake..
  v_mcake_buy =E=   p_fedcrp_mcake_cow  * v_live_cow + p_fedcrp_mcake_buf  * v_live_buffalo
  + v_enbp_mcake + v_mcake_sale   - p_bprcrop_mcake  * p_yldcrop_mustard      * v_mustard_area;

*      Balance on Livestocks

con_livsl_cow..               p_live_cow =G= v_cow_headsale;
con_livsl_buf..               p_live_buffalo =G= v_buf_headsale;
con_livbu_cow..                 v_live_cow =G= p_live_cow + v_cow_headbuy;
con_livbu_buf..                v_live_buffalo =G= p_live_buffalo + v_buf_headbuy;

*      Balance on Livestocks products

con_baliv_milk..    p_prodliv_milk_cow  * v_live_cow + p_prodliv_milk_buf  * v_live_buffalo
  =E= v_cowmilk_sale + p_conliv_cow_milk + v_bufmilk_sale + p_conliv_buf_milk -  v_cowmilk_buy  -
v_bufmilk_buy;

con_baliv_manure..    (p_prodliv_manure_cow  * v_live_cow + p_prodliv_manure_buf  *
v_live_buffalo)* (1-perc_dungtomg)   =E= v_cowmanure_sale + v_bufmanure_sale -
v_cowmanure_buy  - v_bufmanure_buy   + ann_manure_noncrop  +   ann_manure_crop ;

*       Constraint of sale of livestock products
con_balivsl_milk..     p_prodliv_milk_cow  * v_live_cow + p_prodliv_milk_buf  * v_live_buffalo =G=
v_cowmilk_sale + v_bufmilk_sale;

con_balivsl_manure..     (p_prodliv_manure_cow  * v_live_cow + p_prodliv_manure_buf  *
v_live_buffalo)*(1-perc_dungtomg)   =G= v_cowmanure_sale + v_bufmanure_sale;

con_balivsl_bufmilk..    v_bufmilk_sale =L= p_prodliv_milk_buf * v_live_buffalo;
con_balivsl_cowmilk..     v_cowmilk_sale =L= p_prodliv_milk_cow  * v_live_cow;

*       Constraint of purchase of livestock products
con_balivbu_milk..    v_bufmilk_buy + v_cowmilk_buy  =L= p_conliv_cow_milk + p_conliv_buf_milk;

con_balivbu_manure..    v_cowmanure_buy + v_bufmanure_buy   =L= ann_manure_noncrop  +
ann_manure_crop;
```

con_allcrop_manure.. ann_manure_crop + slurry_prod =E= v_frmanur_wheat + v_frmanur_rice + v_frmanur_sugar + v_frmanur_mustard + v_frmanur_potato;

con_wheat_manure.. p_mnrcrp_wheat * v_wheat_area =E= v_frmanur_wheat;
con_rice_manure.. p_mnrcrp_rice * v_rice_area =E= v_frmanur_rice;
con_sugar_manure.. p_mnrcrp_sugar * v_sugar_area =E= v_frmanur_sugar;
con_mustard_manure.. p_mnrcrp_mustard * v_mustard_area =E= v_frmanur_mustard;
con_potato_manure.. p_mnrcrp_potato * v_potato_area =E= v_frmanur_potato;

**** Dung balance for different dung based energy technologies***

con_dung.. (t_dung*3/0.094)/12 + (i_dung*3/0.156)/12 + (bgas_cook*25/0.574)/22 + ((((n_biogas_light * 1000000)/240)/0.574)/22)*25 + ((((d_biogas_light * 1000000)/240)/0.574)/22)*25 + (n_bgas_power*25/0.3)/22 + (d_bgas_power*25/0.3)/22 + (bgas_irrig*25/0.35)/22 =L= ann_manure_noncrop ;

con_dcake.. v_dungcake =E= (t_dung/0.094)*12 + (i_dung/0.156)*12 ;

con_bgas.. v_bgas =E= (bgas_cook/0.574)/22 + (n_bgas_power/0.3)/22 + (d_bgas_power/0.3)/22 + (bgas_irrig/0.35)/22 + (((n_biogas_light * 1000000)/240)/0.574)/22 + (((d_biogas_light * 1000000)/240)/0.574)/22 ;

con_slurry.. slurry_prod =E= bgas_cook*slurry_bgas_ratio + n_bgas_power*slurry_bgas_ratio + d_bgas_power*slurry_bgas_ratio + bgas_irrig*slurry_bgas_ratio + ((n_biogas_light * 1000000)/240)*slurry_bgas_ratio + ((d_biogas_light * 1000000)/240)*slurry_bgas_ratio;

**** Wood balance for different wood based energy technologies***

con_wood.. (t_wood/0.18)/19.71 + (i_wood/0.3)/19.71 =E= v_wood ;

con_wood_balance.. tot_ann_forest*(1-perc_woodtomg) =E= v_wood + v_wood_sale - v_wood_buy;

con_wood_salebalance.. v_wood_sale =L= tot_ann_forest*(1-perc_woodtomg);
con_wood_buybalance.. v_wood_buy =L= v_wood;

**** Crop Residue balance for different crop residue based energy technologies***

con_cropres.. (t_crop/0.098)/15.26 + (i_crop/0.163)/15.26 =L= tot_ann_cropres_nonliv ;

con_cropres_energy.. tot_ann_cropres_nonliv =E= v_enbp_mstraw + v_enbp_sleaves + v_enbp_rstraw + v_enbp_rhusk;

****Energy System balances***

con_totcookdem.. t_dung + i_dung+ t_wood + i_wood+ t_crop+ i_crop+ lpg + bgas_cook + v_enercook_mg =E= tot_cookdem;

con_grid_light_night.. n_grid_light =L= grid_light_current_sup_night ;

con_grid_light_day.. d_grid_light =L= grid_light_current_sup_day ;
con_tot_nightlight.. n_ker_light + n_solbat_light + n_grid_light + n_gridbat_light + n_disgen_light + n_biogas_light + n_lpg_light + v_nlight_mg =E= tot_light_req_night ;

con_tot_daylight.. d_ker_light + d_sol_light + d_grid_light + d_gridbat_light + d_disgen_light + d_biogas_light + d_lpg_light + v_dlight_mg =E= tot_light_req_day ;

con_grid_power_day.. d_grid_power =L= tot_pos_gridpower_day ;

con_grid_power_night.. n_grid_power =L= tot_pos_gridpower_night ;

con_tot_daypower.. d_sol_power + d_solbat_power + d_grid_power + d_gridbat_power + d_disgen_power + d_bgas_power +v_dpower_mg =E= tot_power_req_day ;

con_tot_nightpower.. n_solbat_power + n_grid_power + n_gridbat_power + n_disgen_power + n_bgas_power +v_npower_mg =E= tot_power_req_night;

con_tot_irrigation_energydemand.. swp_irrig + dis_irrig + grid_irrig + bgas_irrig + marketwater_irrig + v_irrig_mg =E= p_irrigener_wheat * v_wheat_area + p_irrigener_rice * v_rice_area + p_irrigener_sugar * v_sugar_area + p_irrigener_mustard * v_mustard_area + p_irrigener_potato * v_potato_area ;

con_HHlabmale_energy.. v_labbp_male_energy =E= v_labbp_male_rstraw + v_labbp_male_sleaves + v_labbp_male_mstraw + v_labdngcake_male + v_labbgas_male + v_labenwood_male ;

**** Household annual expense from its household energy system (in Rs)***

con_tot_ener_expense.. v_tot_ener_expense =E= t_dung*p_tdung + i_dung*p_idung + t_wood*p_twood + i_wood*p_iwood + t_crop*p_tcrop + i_crop*p_icrop + lpg*p_lpg + bgas_cook*p_bgascook + n_ker_light*p_ker_n + n_solbat_light*p_n_solbatlight + n_grid_light*p_n_gridlight + n_gridbat_light*p_n_gridbatlight + n_disgen_light*p_n_disgenlight + n_biogas_light*p_n_biogaslight + n_lpg_light*p_lpglight + d_ker_light*p_ker_n + d_solbat_light*p_n_solbatlight + p_sollight*d_sol_light + d_grid_light*p_n_gridlight + d_gridbat_light*p_n_gridbatlight + d_disgen_light*p_n_disgenlight + d_biogas_light*p_n_biogaslight + d_lpg_light*p_lpglight + d_sol_power*p_sol_power + d_solbat_power*p_solbat_power + d_grid_power*p_gridpower + d_gridbat_power*p_gridbat_power + d_disgen_power*p_disgen_power + d_bgas_power* p_bgas_power + n_solbat_power*p_solbat_power + n_grid_power*p_gridpower + n_gridbat_power*p_gridbat_power + n_disgen_power*p_disgen_power + n_bgas_power* p_bgas_power + swp_irrig*p_swp_irrig + dis_irrig*p_dis_irrig + grid_irrig*p_grid_irrig + bgas_irrig* p_bgas_irrig + marketwater_irrig*p_marketwater_irrig + v_enercook_mg*pric_enercook_mg + v_dlight_mg*pric_dlight_mg + v_nlight_mg*pric_nlight_mg + v_dpower_mg*pric_dpower_mg + v_npower_mg*pric_npower_mg + v_irrig_mg*pric_irrig_mg ;

Household's annual health costs from its energy system (in Rs)

con_healthcost.. t_dung*hdamage_tdung + i_dung*hdamage_idung + t_wood*hdamage_twood + i_wood*hdamage_iwood + t_crop*hdamage_tcrop + i_crop*hdamage_icrop + lpg*hdamage_lpg + bgas_cook*hdamage_bgas + n_ker_light*hdamage_ker + n_solbat_light*hdamage_solbatlight + n_grid_light*hdamage_gridlight + n_gridbat_light*hdamage_gridbatlight + n_disgen_light*hdamage_disgenlight+ n_biogas_light *hdamage_bgaslight + d_ker_light*hdamage_ker + d_sol_light*hdamage_sollight + d_solbat_light*hdamage_solbatlight + d_grid_light*hdamage_gridlight + d_gridbat_light*hdamage_gridbatlight + d_disgen_light*hdamage_disgenlight+ d_biogas_light *hdamage_bgaslight + d_sol_power*hdamage_sol + d_solbat_power*hdamage_sol + d_grid_power*hdamage_grid + d_gridbat_power*hdamage_grid + d_disgen_power*hdamage_disgen + d_bgas_power*hdamage_bgaspower + n_bgas_power*hdamage_bgaspower + n_solbat_power*hdamage_solbat + n_grid_power*hdamage_grid + n_gridbat_power*hdamage_gridbat + n_disgen_power*hdamage_disgen + swp_irrig*hdamage_sol + dis_irrig*hdamage_disgen + grid_irrig*hdamage_grid + bgas_irrig* hdamage_bgaspower + marketwater_irrig*hdamage_grid =E= tot_healthcost;

**** Annual Carbon dioxide emissions from its energy system (in kgs)***

con_co2emis.. (t_dung*1.13 + i_dung*0.81 + t_wood*0.54 + i_wood*0.34 + t_crop*1.01 + i_crop*0.80 + lpg*0.12 + bgas_cook*0.14 + n_ker_light*7071.32 + n_solbat_light*0 + n_grid_light*0 + n_gridbat_light*0 + n_disgen_light*10.23 + n_biogas_light *612.67 + d_ker_light*7071.32 + d_sol_light*0 + d_grid_light*0 + d_gridbat_light*0 + d_disgen_light*10.23 + d_biogas_light *612.67 + d_sol_power*0 + d_solbat_power*0 + d_grid_power*0 + d_gridbat_power*0 + d_disgen_power*0.21 + d_bgas_power*0.016 + n_solbat_power*0 + n_grid_power*0 + n_gridbat_power*0 + n_disgen_power*0.21 + n_bgas_power*0.05 + swp_irrig*0 + dis_irrig*0.21 + grid_irrig*0 + bgas_irrig * 0.054 + marketwater_irrig*0)/1000 =E= tot_co2emis;

**** Per unit energy price on cooking, lighting, power and irrigation (Rs/ unit)***

con_cookenergy_price.. cook_energy_price =E= (t_dung*p_tdung + i_dung*p_idung + t_wood*p_twood + i_wood*p_iwood + t_crop*p_tcrop + i_crop*p_icrop + lpg*p_lpg + bgas_cook*p_bgascook + v_enercook_mg*pric_enercook_mg)/ tot_cookdem ;

con_daypower_price.. day_power_price =E= (d_sol_power*p_sol_power + d_solbat_power*p_solbat_power + d_grid_power*p_gridpower + d_gridbat_power*p_gridbat_power + d_disgen_power*p_disgen_power + d_bgas_power*p_bgas_power + v_dpower_mg*pric_dpower_mg)/ tot_power_req_day ;

con_nightpower_price.. night_power_price =E= (n_solbat_power*p_solbat_power + n_grid_power*p_gridpower + n_gridbat_power*p_gridbat_power +

n_disgen_power*p_disgen_power + n_bgas_power*p_bgas_power + v_npower_mg*pric_npower_mg)/ tot_power_req_night ;

con_nightlight_price.. night_light_price =E= (n_ker_light*p_ker_n + n_solbat_light*p_n_solbatlight + n_grid_light*p_n_gridlight + n_gridbat_light*p_n_gridbatlight + n_disgen_light*p_n_disgenlight + n_biogas_light*p_n_biogaslight + v_nlight_mg*pric_nlight_mg)/ tot_light_req_night;

con_irrig_ener_price.. irrig_ener_price =E= (swp_irrig*p_swp_irrig + dis_irrig*p_dis_irrig + grid_irrig*p_grid_irrig + bgas_irrig*p_bgas_irrig + marketwater_irrig*p_marketwater_irrig + v_irrig_mg*pric_irrig_mg)/ tot_irrig_energ_req;

Model definition

Model BAU /
obj,
budget,
con_budget,
con_offrm_male,
con_offrm_female,
con_offrm_child,
con_land_wheat,
con_land_rice,
con_land_sugar,
con_land_mustard,
con_land_potato,
con_land_winter,
con_land_summer,
con_laborHH_male,
con_laborHH_female,
con_laborHH_child,
con_labrice,
con_labwheat,
con_labsugar,
con_labmustard,
con_labpotato,
con_lablivcowbal,
con_cowbal,
con_lablivbufbal,
con_bufbal,
con_labenbp_rstraw,
con_labenbp_sleaves,
con_labenbp_mstraw,
con_laben_dungcake,
con_laben_bgas,

con_labenwood,
con_laboroffarm_male,
con_laboroffarm_female,
con_laboroffarm_child,
con_labagrifrmout_male,
con_labagrifrmout_female,
con_labagrifrmout_child,
con_cropbal_wheat,
con_cropbal_rice,
con_cropbal_sugar,
con_cropbal_mustard,
con_cropbal_potato,
con_balslcrp_wheat,
con_balslcrp_rice,
con_balslcrp_sugar,
con_balslcrp_mustard,
con_balslcrp_potato,
con_balbucrp_wheat,
con_balbucrp_rice,
con_balbucrp_sugar,
con_balbucrp_mustard,
con_balbucrp_potato,
con_bprbal_rstraw,
con_bprbal_rhusk,
con_bprbal_wstraw,
con_bprbal_stop,
con_bprbal_sleaves,
con_bprbal_must,
con_bprbal_mcake,
con_balslbp_rstraw,
con_balslbp_rhusk,
con_balslbp_wstraw,
con_balslbp_stop,
con_balslbp_mstraw,
con_balslbp_mcake,
con_balslbp_sleaves,
con_balbubp_rstraw,
con_balbubp_rhusk,
con_balbubp_wstraw,
con_balbubp_stop,
con_balbubp_sleaves,
con_balbubp_sleaves_max,
con_balbubp_mstraw,
con_balbubp_mcake,
con_livsl_cow,

con_livsl_buf,
con_livbu_cow,
con_livbu_buf,
con_baliv_milk,
con_baliv_manure,
con_balivsl_milk,
con_balivsl_bufmilk,
con_balivsl_cowmilk,
con_balivsl_manure,
con_balivbu_milk,
con_balivbu_manure,
con_allcrop_manure,
con_wheat_manure,
con_rice_manure,
con_sugar_manure,
con_mustard_manure,
con_potato_manure,
con_dcake,
con_bgas,
con_cropres_energy,
con_dung,
con_slurry,
con_wood,
con_cropres,
con_totcookdem,
con_grid_light_night,
con_grid_light_day,
con_tot_nightlight,
con_tot_daylight,
con_grid_power_day,
con_grid_power_night,
con_tot_daypower,
con_tot_nightpower,
con_tot_irrigation_energydemand,
con_HHlabmale_energy,
con_tot_ener_expense,
con_healthcost,
con_co2emis,
con_wood_balance,
con_wood_salebalance,
con_wood_buybalance ,
con_cookenergy_price,
con_daypower_price,
con_nightpower_price,
con_nightlight_price,

con_irrig_ener_price/
;

**** Executing the model***

Solve BAU maximizing v_obj using MIP;

**** Displaying model results on the screen***

display
v_rice_area.L, v_wheat_area.L, v_sugar_area.L, v_mustard_area.L, v_potato_area.L, v_rice_sale.L, v_wheat_sale.L, v_sugar_sale.L, v_mustard_sale.L, v_potato_sale.L, v_rhusk_sale.L, v_rstraw_sale.L, v_wstraw_sale.L, v_stop_sale.L, v_sleaves_sale.L, v_mstraw_sale.L, v_mcake_sale.L, v_cowmilk_sale.L, v_cowmanure_sale.L, v_bufmilk_sale.L, v_bufmanure_sale.L, v_cow_headsale.L, v_buf_headsale.L, v_nonagrilab_male.L, v_nonagrilab_female.L, v_nonagrilab_child.L, v_farmlabout_male.L, v_farmlabout_female.L, v_farmlabout_child.L, v_farmlabin_male.L, v_farmlabin_female.L, v_farmlabin_child.L, v_rice_buy.L, v_wheat_buy.L, v_sugar_buy.L, v_mustard_buy.L, v_potato_buy.L, v_rhusk_buy.L, v_rstraw_buy.L, v_wstraw_buy.L, v_stop_buy.L, v_sleaves_buy.L, v_mstraw_buy.L, v_mcake_buy.L, v_cowmilk_buy.L, v_cowmanure_buy.L, v_bufmilk_buy.L, v_bufmanure_buy.L, v_cow_headbuy.L, v_buf_headbuy.L, t_dung.L, i_dung.L, t_wood.L, i_wood.L, t_crop.L, i_crop.L, lpg.L, bgas_cook.L, slurry_prod.L, n_ker_light.L, n_solbat_light.L, n_grid_light.L, n_gridbat_light.L, n_disgen_light.L, *n_gasifier_light.L, n_biogas_light.L, n_lpg_light.L, d_ker_light.L, d_solbat_light.L, d_grid_light.L, d_gridbat_light.L, d_disgen_light.L, *d_gasifier_light.L, d_biogas_light.L, d_lpg_light.L, d_sol_light.L, n_solbat_power.L, n_grid_power.L, n_gridbat_power.L, n_disgen_power.L, n_bgas_power.L, *n_gasifier_power.L, d_sol_power.L, d_solbat_power.L, d_grid_power.L, d_gridbat_power.L, d_disgen_power.L, d_bgas_power.L, *d_gasifier_power.L, swp_irrig.L, dis_irrig.L, grid_irrig.L, bgas_irrig.L, marketwater_irrig.L, tot_ann_cropres_nonliv.L, ann_manure_noncrop.L, ann_manure_crop.L, v_budg.L, v_labrice_male.L, v_labwheat_male.L, v_labsugar_male.L, v_labmustard_male.L, v_labpotato_male.L, v_labliv_male_cow.L, v_labliv_male_buffalo.L, v_labbp_male_rstraw.L, v_labbp_male_sleaves.L, v_labbp_male_mstraw.L, v_labdngcake_male.L, v_labbgas_male.L, v_labenwood_male.L, v_labrice_female.L, v_labwheat_female.L, v_labsugar_female.L, v_labmustard_female.L, v_labpotato_female.L, v_labliv_female_cow.L, v_labliv_female_buffalo.L, v_labbp_female_rstraw.L, v_labbp_female_sleaves.L, v_labbp_female_mstraw.L, v_labdngcake_female.L, v_labbgas_female.L, v_labenwood_female.L, v_labrice_child.L, v_labwheat_child.L, v_labsugar_child.L, v_labmustard_child.L, v_labpotato_child.L, v_labliv_child_cow.L, v_labliv_child_buffalo.L, v_labbp_child_rstraw.L, v_labbp_child_sleaves.L, v_labbp_child_mstraw.L, v_labdngcake_child.L, v_labbgas_child.L, v_labenwood_child.L, v_farmlabout_child.L, v_enbp_rhusk.L, v_enbp_rstraw.L, v_enbp_sleaves.L, v_enbp_mstraw.L, v_enbp_stop.L, v_enbp_wstraw.L, v_enbp_mcake.L, v_dungcake.L, v_bgas.L, *v_wood.L, v_frmanur_wheat.L, v_frmanur_rice.L, v_frmanur_sugar.L, v_frmanur_mustard.L, _frmanur_potato.L, v_live_cow.L, v_live_buffalo.L, v_obj.L, v_labbp_male_energy.L, v_tot_ener_expense.L, v_enercook_mg.L, v_nlight_mg.L, v_dlight_mg.L, v_npower_mg.L, v_dpower_mg.L, v_irrig_mg.L, tot_healthcost.L tot_co2emis.L, v_wood.L, v_wood_sale.L, v_wood_buy.L ;