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CLEAN AND EFFICIENT ENERGY SYSTEMS IN SLUMS TRANSFORMATION:

THE CASE OF SOUTH ASIA AND SUB-SAHARAN AFRICA

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ABSTRACT OF DISSERTATION

submitted by:

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The combination of rapid urbanization and increasing wealth in developing countries, particularly in Sub-Saharan Africa (SSA) and South Asia (SA), may have an extremely negative impact on climate change. The positive trend of increased wealth leads to higher energy and resource consumption unless it is channeled towards climate-friendly development. However, at the same time, due to the inability of city governments to plan and provide affordable housing for the low-income segments of the urban population results in an increase of the concentration of urban poor or slums. The existence of slums is a crucial element of contemporary urbanization.

The academic community and policy makers have acknowledged the acute need and associated challenges to provide adequate quality energy services to urban poor and enable their development in sustainable ways. However, the strategies and policies to tackle these challenges are yet to be fully understood especially in terms of reducing the adverse impacts on the environment while ensuring the provision of these energy services needed for their development. Since urbanization is projected to be very fast in the next few decades this is where carbon lock-in has to be avoided by early action towards sustainable urbanization. This research work aims to fulfill the above gap in knowledge and therefore supports the dual aims of applied policy impact and intellectual leadership.

The aim of this research is to provide a picture of the possible slum development futures from energy perspective that may help governments, policy makers and organizations to choose and prepare for the desired urban future. This aim is achieved by estimating the final energy savings, and greenhouse gas emissions reduction potential of the slum households in 52 out of 57 countries in SSA and SA from the application of efficient technologies in the efficient scenario against the reference scenario until 2040. The study uses a bottom-up approach i.e. calculating final energy demand by end use on the level of individual households and aggregating these figures to the whole slum population. It includes detailed technological information for end-uses. Long range Energy Alternatives Planning System (LEAP) model is used for the analysis.

The dissertation concludes that final energy savings from all regions in 2040 by achieving the efficient scenario is 474 billion kWh. The results suggest that overall 67% final energy savings can be achieved in 2040 from all end-uses and energy sources compared to the reference scenario. Cumulatively 46% final energy savings (5260 Billion Kilowatt-Hours) can be achieved in the study period (2014-2040) from the efficient scenario while all basic energy needs are fully met. A total reduction of 58 million tonnes GHG emissions are realized by the efficient scenario in 2040. The total cumulative GHG emissions reduction of 550 million tonnes CO_2e can be realized during the study period by the efficient scenario. When compared to the reference scenario, energy savings and emission reduction potential are significant. Even though 550 million tonnes or roughly half a gigaton GHG emissions reduction achieved in the study period may seem small from the global environmental perspective, the dissertation has shown that the developmental benefits or co-benefits as a result of these energy efficiency actions are critical for the achievement of the Sustainable Development Goals (SDGs).

The above results inform that both environmental and developmental objectives can be achieved by providing clean and sustainable energy sources to slum households. Communicating the role of developmental benefits that the mitigation action brings are hence important in terms of gaining traction for the effective climate change mitigation action. Further, in order to achieve the efficient scenario, slum upgrading programs should be integrated with the fuel subsidies together with appliance standards, labeling, and financing schemes (to meet the challenge of high upfront cost of efficient appliances). In essence, the research aims to connect the dots between the Paris Agreement, SDGs and New Urban Agenda, in order to build a sustainable urban roadmap that brings the global urban poor community towards a better future.

Keywords: Urbanization, Slums, Energy Services, Scenario Analysis

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List of Abbreviations

CFL	Compact Fluorescent Lamp
GWP	Global Warming Potential
GHG	Greenhouse Gas
IAMs	Integrated Assessment Models
IEA	International Energy Agency
INDCs	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
LED	Light-Emitting Diode
LPG	Liquid Petroluem Gas
LEDS	Low-Emission Development Strategies
LEAP	Long range Energy Alternatives Planning System
MDGs	Millennium Development Goals
NAMA	Nationally Appropriate Mitigation Actions
SDGs	Sustainable Development Goals
SLCPs	Short-Lived Climate Pollutants
SSA	Sub-Saharan Africa
SA	South Asia
SEI	Stockholm Environment Institute
UEC	Unit Energy Consumption
UNESCO	United Nations Educational Scientific and Cultural Organisation
WEO	World Energy Outlook

Chapter Outlines

CLEAN AND EFFICIENT ENERGY SYSTEMS IN SLUMS TRANSFORMATION: THE CASE OF SOUTH ASIA AND SUB-SAHARAN AFRICA

Chapter1. Introduction

The introduction provides an overview of the overall research, the importance, research questions and objectives, scope, and practical contribution in terms of policy impact and intellectual leadership. It argues that in the context of rapid urbanization, economic growth and climate change the energy uses of slum households are set to increase fast and that is a strong rationale to provide them sustainable energy. The overall research question concerns with the finding out the magnitude of total final energy savings, and GHG emission reduction potential of slums transition to efficient energy systems. It briefly describes the research method, limitations, and is concluded by the outlining of thesis structure.

Chapter 2. Energy demand of slums in the context of rapid urbanization

The objective of this chapter is twofold a) to examine the current energy uses among slum households, and b) to provide analysis of slum programs and strategies from housing perspectives and evaluate their effectiveness in sustainable energy provision. The chapter is an inquiry that intends to assess the current levels of access to all forms of energy to the slum households, and policies and strategies from housing perspective with special emphasize on making slum upgrading practices more sustainable from energy perspective in the age of urbanization and climate change. The chapter starts with defining the slums and regions experiencing rapid urbanization where these slum populations live and according to the projection which will keep on urbanizing for the decades to come. Then it elaborates on energy access problems among slum dwellers which are described with the use of energy services ladder concept and then current energy use patterns. Next, slum policies and strategies from housing perspective are described with emphasis on slum upgrading, and a lack of focus on providing sustainable and clean energy to slum dwellers. Finally, futures of slums are envisioned keeping in view of prevalent trends and best practices if they become the norm.

Chapter 3. Theoretical Framework

The chapter provides modeling literature review by elaborating various modeling techniques applied to forecast residential energy demand in general as well as from the perspective of developing countries. This is with the objective to understand the type of model most suitable for the present research and also to learn from their shortcomings and advantages. Cities in developing countries are increasing in importance as the global community aims to remain below the 1.5°C emissions level. Therefore a review is also undertaken from developing countries perspectives pertinent to the topic of the dissertation.

Chapter 4. Research Design and Methodology

The chapter describes the research design and the methodology used in the dissertation. First, methodological approach is described in terms of a function of activity level, energy intensity, and efficiency. A simplified structure of the modeling framework for slum households' context is presented and a flowchart of appliances energy savings and CO_2e mitigation calculation is given to describe the modeling process. Next, reference and efficient scenarios and what they entail, slum population growth rate calculation, modeling method and drivers of energy use, and core equations are detailed. Further, end-use diffusion (activity level) methodology, energy intensity calculation for the end-uses, and final energy demand analysis are provided. The chapter also gives information about data sources and limitations of the applied modeling approach.

Chapter 5. Final Energy Saving Potential

This chapter is in line with fulfilling the research gap in knowledge by providing evidence-based energy efficient pathways in urban poor context. The chapter starts off with estimating the level of current end-use demand, and to forecast growth in slums energy demand until 2040 by end use in the reference scenario. Next, the efficient scenario is created by introducing efficient appliances and forecasting the energy demand until 2040. By comparing the two scenarios, the magnitude of the energy savings from slums transition to efficient energy system is obtained. Overall final energy demand and savings are calculated using the same approach as shown by India example. Research results are described in terms of the energy savings of the slum households on the level of individual end-uses in Sub-Saharan Africa and South Asia from the application of efficient technologies in the efficient scenario (desirable) against the reference scenario until 2040. To check the validity of the results, calibration in the base year is carried out.

Chapter 6. Greenhouse Gas emissions reduction potential

In the context of rapid urbanization and increasing number of slum households, it is a pertinent question to find out how large are the Greenhouse Gas (GHG) emissions reduction potential of achieving the efficient scenario. This chapter details the calculation method of GHG emissions, provide estimates of the emissions in the reference and the efficient scenario, and emissions reduction potential lie in the efficient scenario. I also select few countries from the study regions to show their emission trajectories based on how their slum population, appliance diffusion, and unit energy consumption grow over the study period.

Chapter 7. Discussion: Mitigation within a development context

The chapter describes the major findings from the analysis that environmental and developmental objectives go hand in hand by providing efficient energy end-uses to urban poor. The chapter builds its argument from the research results that current energy uses from slum households are not significant compared to non-slum households. However, in the context of rapid urbanization, economic growth and climate change the energy uses of slum households are expected to grow fast and may even reach the regional averages for many countries soon. Therefore, communicating why climate action associated with mitigation could have developmental advantages is crucial to gain traction for the effective climate change mitigation action. The chapter strengthens the viewpoint that doing so a future that is necessarily low carbon but that also fulfills human desires of a good life can be achieved. Further, in the chapter, I look deeper into the key challenges and potential solutions for realizing the efficient scenario, discuss the policy relevancy of the research such as assessing the level of entry points at which policies will need to be introduced to be more successful.

Chapter 8: Conclusions

The section provides a summary of the main findings and contributions of this research study. It describes implications of the research for the policy design and academic knowledge contribution. Transferable lessons and recommendations are formulated. The chapter also identifies the opportunities for future research, for example, to complement this regional study with a country or city level study to get a more detailed treatment of the topic.

Chapter 1. Introduction

1.1 Urban transformation

It is well recognized that humans have driven the planet into a new geological epoch – Anthropocene (Crutzen 2002, Rockstrom and Kargrlbe 2010). Anthropogenic climate change has become a central issue worldwide. There is a consensus now that rapid global warming by more than 2°C would overburden societies' capacity to adapt. In order to restrict global warming to a mean temperature change of 2°C, a fast transformative counteraction is required. In the words of Westley et al. (2011) – "…the transformative development may require radical, systemic shifts in deeply held values and beliefs, patterns of social behavior, and multi-level governance and management regimes". Therefore the global energy system must fundamentally be decarbonized by 2050 (WBGU, 2011). However, apart from being the solution for climate change problem, the energy system transformation would also bring developmental benefits to the large part of the society especially that lack sustainable forms of energy access. In the context of rapid urbanization, economic growth and climate change the energy uses of slum households are set to increase fast and that is a strong rationale to provide them sustainable energy. The dissertation examines the energy and emissions impact pathways of urban transformation from urban poor context. It further estimates energy savings and emission reduction potential of realizing the efficient energy pathway.

In the developing world, a massive urban transformation is taking place in the form of urbanization. It is evident that most of the growth in the world's population for the near future will take place in cities and towns of the developing world (UN Habitat, 2009). Urbanization is quite new global phenomena. Only 30% of the world's population was urban in 1950 (ibid). Today more than half of the world's total population is living in the cities (UN 2014). The trend of urbanization is global but with differing rates varied by country and regions. Today's developed countries were mostly urban by the 1950s. However, the group of less developed countries will only reach to this level of urbanization until 2019 (UN DESA, 2011). It is projected that in around 2050, about 70% of the world's population will be urban (UNDESA, 2011; figure 1). The majority of the developing countries will become more urban than rural for the first time in the next twenty years (Montgomery et al., 2003). At the start of the twentieth century, only 16 cities mainly from the advanced industrial economies in the world had a million people or more. Today, there are more than 400 cities are of this size and most of them are found in low and middle-income countries (Montgomery et al., 2003, UNESCAP, 2008). Developing countries urban growth is projected to be twice as fast as OECD countries in the 2005-2030 periods (UNESCAP, 2008).

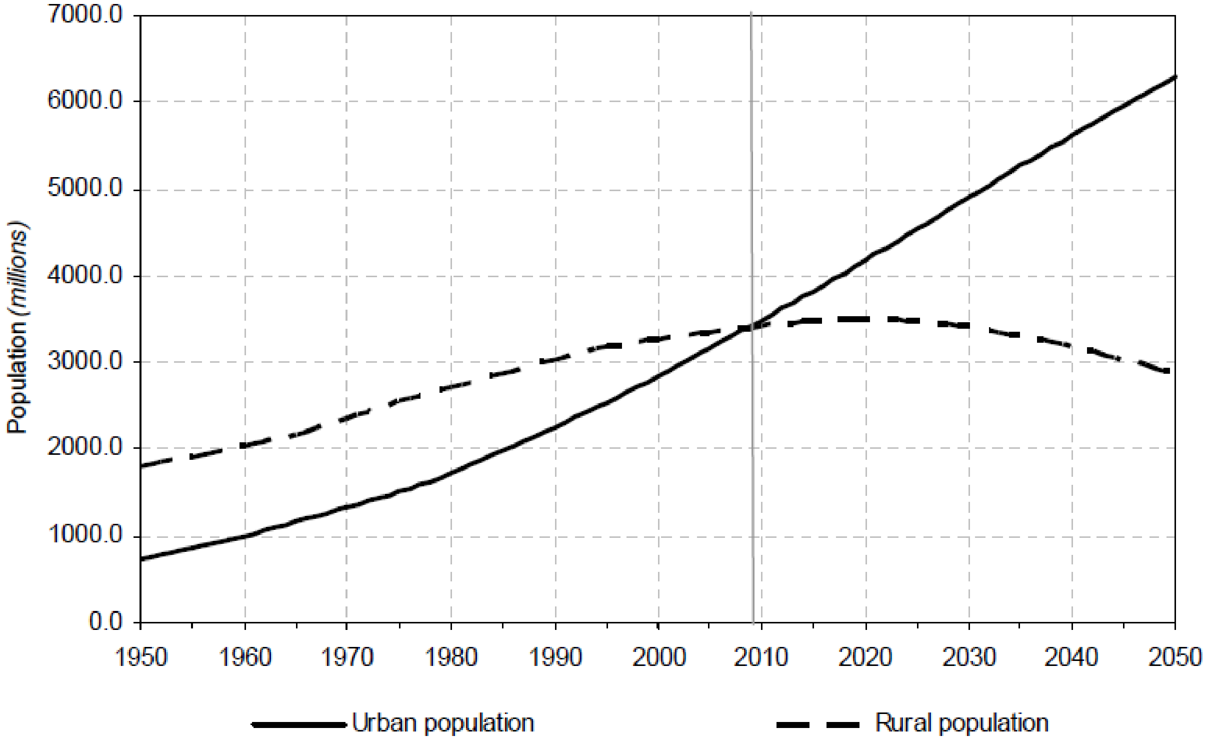

Figure 1 Urban and rural populations of the world, 1950-2050 (Source: UNDESA, 2011)

Historically, urban growth follows the trend of economic growth (UN Habitat, 2010). Gradually cities and urban regions' importance are being recognized as the major engines of economic growth, job creation, and innovation. Urbanization helps in reducing poverty by generating new opportunities, raising incomes and by increasing the numbers of livelihood options (UN Habitat, 2010). Conversely on the flip side, when accompanied by weak economic growth and ineffective or absent distributive policies, the outcome of urbanization is increasing the concentration of poor people termed as slum population rather than poverty reduction (ibid). The existence of slums is a crucial element of contemporary urbanization (Bolay 2006). These poor people join urban areas for the search of a better life mainly migrating from rural areas. These new migrants can expand squatter settlements and shanty towns; worsen the problems of overcrowded neighborhoods, inadequate housing, pollution, and poor access to clean water, sanitation and other basic social services (Montgomery et al., 2003). Each year around 70 million people move to cities in the developing world (UN Habitat 2003). This creates enormous pressure on cities to provide urban infrastructure, services, and safe land.

1.2 Urbanization and energy demands from the slums

Urbanization process is the major driving force behind energy demand in the buildings end use sector and hence synonymous with development (USAID, 2011). New long-lasting infrastructures are created as a result of the urban expansion that is going to impact on the energy demand for a long time to come (UN-Habitat, 2009). With increasing economic growth in developing countries, ownership of energy using assets is increasing to provide the opportunity to benefit from more energy services such as refrigerator, washing machine and air-conditioning (Wolfram et al., 2012). The positive trend of increased wealth leads to higher energy and resource consumption unless it is channeled towards climate-friendly development. Cities of developing countries will be responsible for around 70% of the potential growth in thermal energy use by 2050 (Ürge-Vorsatz et al., 2012). Therefore building energy efficiency efforts should be oriented towards urban areas in developing countries particularly the energy needs of urban poor has to be met sustainably. Current energy uses from slum households are not much compared to non-slum households. However, in the context of rapid urbanization, economic growth and climate change the energy uses of slum households are expected to grow fast and may even reach the regional averages for many countries soon. The magnitude of energy savings, and GHG emission reduction potential of slums transition to efficient energy systems are not known. This research is one step in that direction to find out the energy savings, and

GHG emission reductions if efficient energy end uses are employed by slum households by 2040 using scenario analysis.

The research focuses on the commonalities that slum dwellers share worldwide than regional heterogeneity among them. For instance, most of the slum dwellers come to the city by choice for seeking better employment opportunities. They bring their socio-cultural practices when they first arrive at city but gradually integrate with the city. At first, they leave their families at rural homes and later invite their families when they are in a position to support them. In terms of energy usage they first start with using biofuels for cooking but with time they move upward in the energy ladder and choose kerosene and later LPG that marks their integration with the urban society (WEF 2014). Pachauri et al. (2012) looked at the synergies between energy efficiency and energy access policies and strategies. They found that by building in efficiency criteria at the very beginning of providing access, effective energy supply is reduced significantly, the level and quality of energy services is also improved and cost minimized. They further note that poor households in developing countries (including slum households) are extremely first cost sensitive and often do not make economic optimal choices that result in long-term benefits. Poor households generally unable to value future savings even in light of extra benefits per unit of investments on efficient energy products.

1.3 Research aim, goal, questions, objectives, and scope

The aim of this research is to provide a picture of the possible slum development futures from energy perspective that may help governments, policy makers and organizations to choose and prepare for the desired urban future. The aim requires achieving a specific research goal which is to find out the magnitude of total energy savings, and GHG emission reduction potential of slums transition to efficient energy systems.

Achieving the above aim and goal requires to answer the following research questions and objectives.

1. What is the level of current end-use demand, and to forecast how much growth in slums energy demand will occur until 2040?

Objective 1.1: To forecast appliance diffusion and gather estimates of average unit energy consumption (UEC) in the base year and reference scenario

Objective 1.2: To calibrate model results with the existing studies

2. What are the energy and GHG savings potential of slums from the realization of efficient scenario as compared to the reference scenario?

Objective 2.1: To forecast appliance diffusion and gather estimates of UEC in efficient scenario

Objective 2.2: To evaluate energy and GHG emissions saving potential as a difference between these two scenarios

Countries in Sub-Saharan Africa (SSA) and South Asia (SA) are the most important where slum dynamics will be played most pronounced in the coming decades which make them ideal regions to study. SSA and SA are the least urbanized regions in the world. Only 39.1% of the SSA and 30% of the SA population lives in cities. However, the regions' urban population and thus slum population is projected to increase sharply in the near future. Hence selecting these two world regions would increase the effectiveness of the research results for policy-makers in developing countries to assist the development of their low carbon growth strategies. The end-uses covered in the analysis are cooking, lighting, space cooling (fan), and appliances (television, refrigerator). Biomass, kerosene, and charcoal are the stove types that are used for cooking. Incandescent, fluorescent lamps and LEDs are considered for lighting end use. Dominant types of currently used inefficient and potential efficient appliances are considered for fan, television, and refrigerator end-uses. Slum dynamics will be most prominent in the next two to three decades. The type of development patterns that these slum households will follow during this period will have great influence on the sustainability of the urban future. Due to this reason the target year is chosen as 2040.

1.4 Justification: Gaps addressed and practical contribution

Historically developing countries were considered important in terms of adaptation only but now it is recognized that to reduce the impacts of climate change their emissions have to be reduced while they pursue socio-economic development. Emerging economies are still developing. Currently majority of the world's poor live in the emerging countries. However, communicating why climate action associated with mitigation could have developmental advantages is crucial to gain traction for the effective climate change mitigation action. Therefore there is a need for a new conversation on the challenge of 'mitigation within a development context' or a future that is necessarily low carbon but that also fulfills human desires of a good life (Parnell 2014).

The energy consumption of developing countries has often been lower and hence considered less important than the developed countries. However currently these countries are growing rapidly in a way their energy use is increasing considerably (McNeil et al., 2008). Most importantly poor and near-poor populations (including urban poor) of developing countries are in the forefront as they come out of poverty their energy use increases dramatically (Wolfram et al., 2012). Therefore it is important to forecast the development of future energy use of urban poor population in the developing world. Developed countries have already taken significant measures to increase energy efficiency but developing countries are lagging far behind in this regard especially poor people in these regions still choose inefficient energy products once they are able to afford them. Due to this reason much of the scope of improvement to reap the 'low hanging fruit' is in the developing countries (McNeil et al., 2008).

Academic community and policy makers have acknowledged the acute need and associated challenges to provide quality energy services to urban poor in sustainable ways (Karekezi and Onguru 2008). However, the strategies and policies to tackle these challenges are yet to be fully understood. Therefore the information which can lead to more understanding of the development of such policies and strategies are highly valuable to developing countries. The information that comes from the research may also provide useful insights in designing future slum development policies and programs to policy makers and organizations. This information requires projecting the energy use of urban poor households and subsequent greenhouse gas (GHG) emissions, sustainable alternatives exist to minimize these trends, and the achievement of energy savings in realizing such alternatives. This research work aims to fulfill the above gap in knowledge by providing evidence-based energy efficient pathways in urban poor context. The scenarios used in the research could act as a planning tool and provide insights into suitable strategies and policies that need to be implemented and adopted in order to influence energy use and development in a more sustainable ways in the future.

Another importance of the dissertation is this that it provides estimates of the energy savings and GHG emissions reduction potential from slum households so that the studied countries are well-situated to pursue the mitigation options that are consistent with their own goals and priorities and not dictated by the international profit-seeking mechanisms such as project funding bodies acting upon the international carbon markets motives to explore least-cost mitigation options that may not provide broader societal benefits. At the same time, the research contributes in engaging with the methodological challenges associated.

1.5 Research Method

Modeling is a very data intensive process and the data limitations in the slums context in the low income and the developing countries are a real limitation. Therefore to address this problem, Long range Energy Alternatives Planning System (LEAP) model that is easy to use with, flexible with data inputs, and can work with fewer data is used for the analysis. The framework of bottom-up, end-use accounting technique is applied using a scenario modeling approach to make projections about the whole slum population. It includes detailed technological information for end-uses. The LEAP model developed by Stockholm Environment Institute (SEI) is used to forecast appliance diffusion (activity level), final demand, energy savings, and GHG emission with the realization of the efficient scenario. One of the main reasons to use LEAP is that it represents developing countries characteristics and economies very well (Bhattacharya and Timilsina 2009; Urban et al 2007, p. 3478). The same model which is primarily used for developed countries does not necessarily reflect developing countries unique characteristics and hence using LEAP for this analysis is appropriate.

Scenario narration and quantification provide useful insights in the designing of the slum energy development program and policies. Scenarios that are used in the dissertation are intended to help in charting out possible futures from slums energy use context. Scenarios that are used in the research are –

- Reference (Ref) scenario - Slum households meet the basic level of energy services fully in 2040. However, the energy demands are met by inefficient appliances.
- Efficient (Eff) scenario – Basic needs of energy are fully met and sustainably in 2040, using efficient appliances. Efficient energy services are integrated into slum upgrading programs so that benefits of meeting energy needs outweigh the environmental penalties.

1.6 Limitations

The research does not aim to provide so much the precise estimates of potential energy savings but as a general idea of their magnitude. For some variables data available at the country level is used into the model to reflect a likely value for the sub-region to which the country belongs. Therefore the results which come out from the study may not precisely reflect the energy savings and GHG emission estimates at the country level. Further, study focusing on more detailed data would give a better indication of energy savings and GHG emissions reduction potential of providing clean and efficient energy sources to urban poor at the national or subnational level.

While the study has not implemented any detailed costing of the efficient scenario, several direct and indirect benefits are associated with the adoption and use of the efficient appliances. A focus on efficiency will lead to substantial net cost savings as a result of energy savings.

The dissertation however has considered the technologies that are more efficient, cost effective, and have the potential to directly improve slum households' lives by providing more energy services with less energy consumption than the dominant technology type they are currently using. Therefore I have not looked at the new innovative models of energy provision and development which are currently being considered which has the potential to further increase savings and emission reductions.

1.7 Structure of the dissertation

A literature review (chapter 2) was done with the aim of understanding the energy use situation among slum households. Review of modeling techniques in general and especially from the developing country context to forecast energy use for the residential sector are described in the chapter 3. Research methodology, data sources and research steps which include estimation of savings in energy, and GHG emission reduction potential of achieving the efficient scenario versus the reference scenario are provided in chapter 4. Results are analyzed in the chapter 5 in terms of the total final energy consumption in the base year, in 2040 for the reference scenario, and the efficient scenario, as well as energy saving potential of achieving the efficient scenario. Chapter 6 deals with the GHG emission reduction potential of realizing the efficient scenario. In chapter 7, the research results are discussed in terms of the importance of sustainable energy provision to slums from environmental and developmental perspectives, challenges and potential entry points of achieving the efficient scenario, and the policy implications of energy efficiency measures from slums context. Finally, a summary of the main findings is given in the concluding chapter 8. The chapter also identifies the opportunities for future research, for example, to complement this regional study with a country or city level study. It also describes implications of the research for the policy design and academic knowledge contribution.

Chapter 2. Energy demand of slums in the context of rapid urbanization

"Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive."

– Former UN Secretary -General Ban Ki-moon

The overall purpose of the chapter is to examine the current energy uses among slum households, and slum programs and strategies from housing perspectives to evaluate their effectiveness in sustainable energy provision. The theory and practice of housing sector development for urban poor, slum housing policies and strategies which have been evolved over the period of time such as eviction, sites, and services, and slum upgrading are reviewed. This review highlights the importance of slum upgrading among many initiatives ran by countries thus far to improve the slums living situation. Slum dwellers energy use patterns have been reported only sporadically in the existing literature. Hence the information is collected on current energy use patterns of slum households and an assessment is also provided by incorporating ongoing and planned energy policy reforms from the context of improving access to clean and sustainable energy services and whether they have addressed the challenges faced by urban poor.

Energy is very important for the holistic development of societies. It is estimated that globally 52% population depend on solid fuels to meet their basic energy needs which are often illegal and unsafe for human health and the environment (Sovacool, 2011, IEA 2009). Provision of modern energy services helps in driving growth by increasing productivity to all income groups. Energy, from a scientific standpoint, is defined as '*the capacity to do work*' (Peet, 1992), underscores an improved quality of life particularly for slum dwellers in developing countries. The type of energy source affects the capacity of energy to perform work.

According to the International Energy Agency (IEA) analysis, about 1.5 billion people do not have access to electricity. IEA predicts that 1.3 billion people will still not have access to electricity in 2030 if the current policies and measures continue which means the absolute number of energy poor are not expected to improve over the next two decades (IEA, 2009). Most of the energy poor live in developing countries especially in South Asia and in Sub-Saharan Sub-Saharan Africa. They depend on inefficient biomass fuels with negative effects on air pollution and health (UN-Habitat, 2010). About three-fourth of the world's commercial energy are consumed in urban areas. Many of the people in acute need of access to modern energy services are located in rapidly growing slums throughout the developing world (UN-Habitat, 2006). Regardless of this, the energy needs of poor households in developing countries are primarily focused on the rural poor (UN-Habitat, 2006, WBGU, 2003).

Modern and clean energy provision is not acknowledged as a basic urban service regardless of its importance from an economic and health perspective and therefore development programs have not addressed it completely. Clean and modern energy access in slums is an important precursor for development and there is a need for concerted efforts to place this up in the urban development agenda. Indoor air pollution from the use of harmful fuels such as biomass and charcoal leads to significant health problems. Collecting biomass fuels, where available, takes time that could be rather spent – in school or at work (Karekezi et al. 2008). The higher recurring cost of inefficient energy using devices coupled with the lack of modern energy sources further becomes a constrain in the development of urban poor households (Hammond et al. 2007). Despite the above-mentioned problems, many of these slum households are reaping the benefits of economic opportunities that a city provides and rising up in the energy ladder. Urban policies or more specifically slum policies and programs can play an important role in facilitating clean and sustainable energy provision among slum households.

The present chapter is an inquiry that intends to assess the current levels of access to all forms of energy to the slum households, and policies and strategies from housing perspective with special emphasize on making slum upgrading practices more sustainable from energy perspective in the age of urbanization and climate change. The chapter starts with defining the slums and regions experiencing rapid urbanization where these slum populations live and according to the projection which will keep on urbanizing for the decades to come. Then it elaborates on energy access problems among slum dwellers which are described with the use of energy services ladder concept and then current energy use patterns. Next, slum policies and strategies from housing perspective are described with emphasis on slum upgrading, and a lack of focus on providing sustainable and clean energy to slum dwellers. Finally, futures of slums are envisioned keeping in view of prevalent trends and best practices if they become the norm.

2.1 Urbanization and slums

According to the United Nations projection (2008), by the year 2050, the urban population will increase from 3.3 billion in 2007 to 6.4 billion in 2050. The more striking fact is that 94 percent of this growth will be absorbed by the urban areas of the less developed regions especially in

Sub-Saharan Africa and South Asia (figure 2). It means the rapid urbanization is primarily taking place in countries with only insufficient capacities for orderly urban planning with investments in non-sustainable infrastructures (UN-Habitat, 2009). Fast growing slums, especially in the townships of developing countries, are a prominent example of this rapid urbanization. Common definitions and the operational definition which is used for data collection purposes are given below. The section ends with a description of regions that are experiencing rapid urbanization.

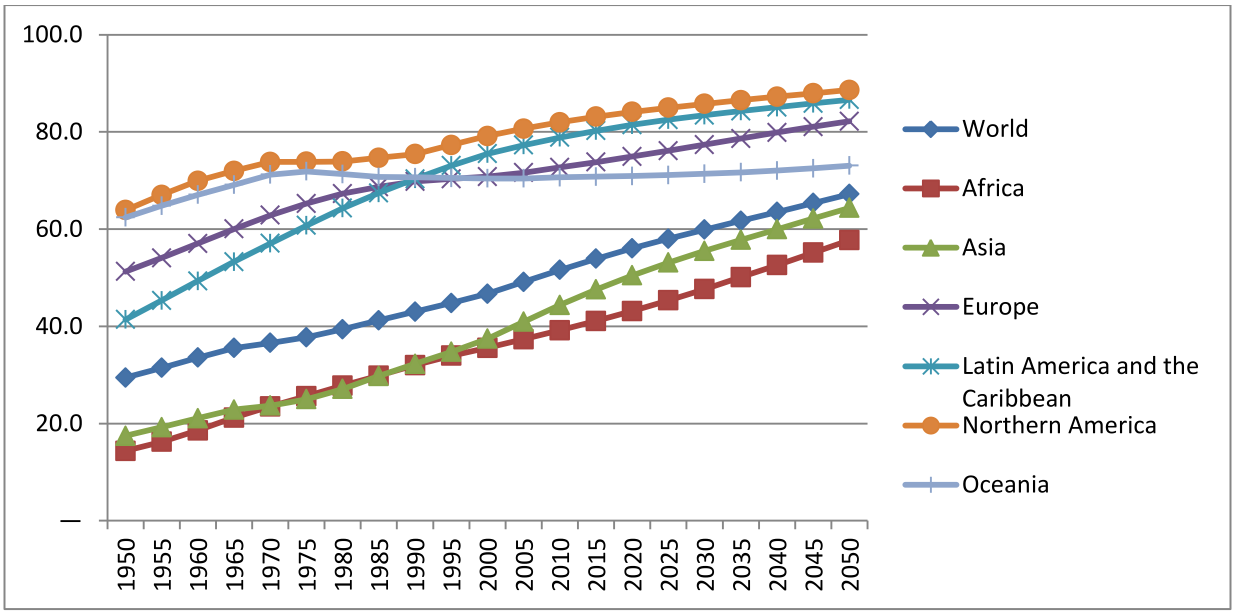

Figure 2: Percentage of urbanization by region, 1950-2050 (Source: UN DESA/Population Division, 2011)

There is a considerable variation in slum definition across countries and regions. The simplest and less technical definition of slum would be – "Slum is a heavily populated urban area characterized by substandard housing and squalor" (UN Habitat 2003). Generally, the term 'slum' is associated with a wide variety of "low-income settlements and poor human living conditions" (UN Habitat, 2003). According to The Cities Alliance action plan – "Slums are neglected parts of cities where housing and living conditions are appallingly poor. United

Nations Educational Scientific and Cultural Organisation (UNESCO) defines slum as – "a contiguous settlement where the inhabitants are characterized as having inadequate housing and basic services". Hence the UNESCO definition highlights slums in terms of an urban space. Slums vary from high density, squalid central city tenements to spontaneous squatter settlements without legal recognition rights, sprawling at the edge of cities" (The Cities Alliance 1999).

These definitions bring forth important characteristics of a slum such as high population density, informality, low standard housing, poverty, lack of legality as well as the possible location in a city. Although these general definitions state what a slum is to some extent, they do not signify an operational definition that can tackle the inconsistencies that arise in practice which create problems in implementing policies and programs to improve slum conditions. Inconsistencies such as identifying areas that can be considered as a slum are enhanced by below features of slums (UN-Habitat 2003b, p.11).

- "Slums are too complex to define according to one single parameter".
- "Slums are a relative concept and what is considered as a slum in one city will be regarded as adequate in another city – even in the same country".
- "Local variations among slums are too wide to define universally applicable criteria".
- "Slums change too fast to render any criterion valid for a reasonably long period of time".
- "The spatial nature of slums means that the size of particular slum areas is vulnerable to changes in jurisdiction or spatial aggregation".

(UN Habitat 2003b, p.11)

There have been efforts after the adoption of “slum goal” in the Millennium Declaration to propose a more operational definition of a slum. The United Nations Human Settlements Programme (UN–Habitat, 2006) defines slum household as “a group of individuals living under the same roof in an urban area who lack one or more of the following five conditions: Access to water; access to sanitation; secure tenure; durability of housing; sufficient living area”. This definition allows determining the number of slum households and helps in evaluating the progress towards accomplishing the development goals. Therefore, this operational definition is used in the dissertation. The United Nations Human Settlements Programme (UN-Habitat) uses the operational definition to come up with the number of slum population currently, live in the world. UN-Habitat data are used for the number of slum population.

Sometimes slums are termed as informal settlements. Informal settlements are defined as “*unplanned settlements and areas where housing is not in compliance with current planning and building regulations*” (Glossary of Environment Statistics, 1997). In most literature, slums and informal settlements, as well as slum dwellers and urban poor, are used interchangeably. In each country, slums are called by different local names such as bidonville, katchi abadi, jhuggi jhoopadi, bustee, favela, barrio, kampung, these either represent materials used in slum construction or rural character from where they move to cities (UN-HABITAT 2003).

It is important to notice that often these non-regulated residential areas are not identified as legal and integral part of the urban areas. Approximately 32% of the world’s urban population (about 924 million people) lived in slums in 2001. Around one in six persons worldwide lives in slums. The majority of the slum population come from developing countries (UN-HABITAT 2003).

South Asia has the largest number of people living in slums followed by Sub-Saharan Africa and Latin America (Cities Alliance 2007). Among the developing regions, Latin America and the Caribbean has the highest level of urbanization (79%) even higher than the Europe (72%) (UN DESA/Population Division, 2011). On the other hand, Sub-Saharan Africa and South Asia remain largely rural. The degree of urbanization will be most evident in Sub-Saharan Africa and South Asia than the rest of the world over the coming decades. This is highlighted by the fact that even by 2050, Sub-Saharan Africa and South Asia are expected to have lower levels of urbanization than more developed regions such as Latin America and the Caribbean. Regardless of this low degree of urbanization, South Asia alone accounted for about half of the urban population in the world. By 2050, most of the urban population will be concentrated in South Asia and Sub-Saharan Africa with 53% and 20% respectively. There are expected to be more urban people than rural by 2023 in South Asia and by 2030 in Sub-Saharan Africa which is referred to as the tipping points (Table 1) (ibid).

Table 1: Degree of urbanization per region and tipping points urban versus rural (UN DESA/Population Division, 2011)

Region	**Tipping point before year 2010**	**Urban (%) Year 2010**	**Tipping point after year 2010**	**Urban (%) 2050**
World		50.6		70
Europe	Before 1950	72.6		83.8
North America	Before 1950	82.1		90.2
Oceania	Before 1950	70.6		76.4
Latin America and the Caribbean	1962	79.4		88.7
Sub-Saharan Africa		40	2030	67
South Asia		42.5	2023	66.2

Slum population projection of developing regions (Figure 3) further highlights the fact that slum population will be the highest in South Asia and Sub-Saharan Africa which will be the realities of urban future.

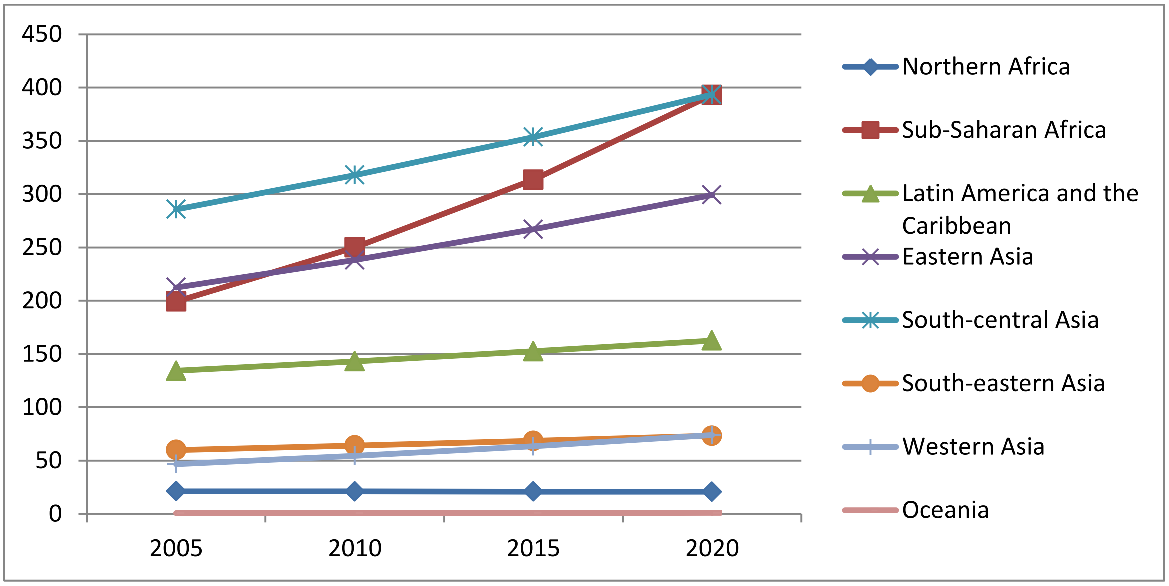

Figure 3: Slum population projection (millions of people) of developing regions until 2020 (UN-HABITAT, 2003)

There are 62% of Sub-Saharan Africa's and 43% of South Asia's urban residents live in slum households. (UN-Habitat, 2009). Overall, almost 1 billion people, or about a third of city dwellers around the world live in slums. Often these slums lack basic urban development standards and legal protection. They frequently have no access to either electricity or clean water, or waste and wastewater disposal facilities (WBGU, 2011). These settlements are often located in relative closeness to the markets and economic activity of cities, thus allowing access to income generation (WBGU, 2011).

According to the slum target of the Millennium Development Goals is to significantly improve the lives of at least 100 million slum dwellers around the world by 2020. A total of 227 million people in the world has moved out of slum conditions since 2000. However in terms of absolute number slum dwellers have actually increased from 776.7 million in 2000 to some 863 million in 2014. Currently, Sub-Saharan Africa has the largest slum population where 199.5 million (or 62%) of its urban population live in such areas. It is followed by Southern South Asia with 190.7 million (35%) and Eastern South Asia with 189.6 million (28%) (UN-Habitat, 2010).

Given the considerable variation in slum definition across countries and regions, an operational definition works best to evaluate development goals set by United Nations and other organizations. However, the more complex social dimensions are left behind and only physical and legal characteristics are taken into account in the operational definition (Arcila 2008). UN-Habitat uses the operational definition to count the slum population hence for the practical reasons it is best suited for the use in this dissertation. Clean and modern energy access in slums is an important precursor for development which is described in the next section.

2.2 Energy access and uses in slums

Modern and clean energy provision has been included as basic needs to achieve sustainable development in the Sustainable Development Goals (SDGs) of United Nations (ICSU, ISSC 2015). Modern and clean energy provision is important for the delivery of basic needs such as food, clean water, shelter, health, and education (Dhingra 2008, GNESD 2013). Firstly, definitions of energy access, and an explanation of incremental levels of energy access are given.

Then energy services ladder that takes place in the context of economic growth is described. Finally, current energy uses of slums are provided.

While there are no set definitions of modern energy access, World Energy Outlook, 2011 (WEO 2011) defines it as - "a household having reliable and affordable access to clean cooking facilities, the first connection to electricity and then an increasing level of electricity consumption over time to reach the regional average" (WEO, 2011). The Secretary General's Advisory Group on Energy and Climate Change (AGECC) defines energy access as – "access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses" (AGECC, 2010).

These broader definitions are in line with access to sufficient energy for basic human needs and productive uses highlight the energy level that is required to improve livelihoods and drives economic development on a sustainable basis in the poorest and developing countries. This is why a shift towards productive uses is so critical: it increases to end users capability to pay for energy services which are vital for the sustainable financial viability of such services. For simplicity, IEA 2009 further divides energy access into three incremental levels, basic human needs, productive uses, and modern society needs –

Level 1: Basic human needs – this includes electricity for lighting, education, health and community services (between 50-100 kWh per person per year) as well as modern fuels and technologies for cooking and heating (between 50-100 kgoe of modern fuel or improved biomass cook stove).

Level 2: Productive uses – this includes energy services for productivity improvement, e.g. irrigation, agricultural processing, transport etc.

Level 3: Modern society needs – this includes increased uses of domestic appliances, cooling and heating, private transportation etc. (around 2000 kWh of electricity usage per person per year).

Providing a "basic human needs" level of energy services will only have a limited impact on greenhouse gas emissions. According to the International Energy Agency (IEA 2009), providing basic universal energy services would add 1.3 % of total global emissions in 2030. However, a shift towards productive uses of energy services could increase emissions considerably (AGECC, 2010). This highlights the importance of enabling fast deployment of energy-efficient end use devices to reduce the amount of energy use. It is even more urgent in the context of increasing number of slum dwellers as they move to the productive uses of energy services with economic growth. The relationship between types of energy services and positive impacts of economic growth on poor households can be understood by energy services ladder concept which is described in the following paragraphs.

People are more interested in the services that energy provides irrespective of the source of energy itself. Energy services generally state what those energy users want such as cooked food, a well-lit room, a warm place to live, a computer with internet connection etc. Therefore energy services can be considered as the "benefits that energy carriers produce for human wellbeing" (Sovacool, 2011). Energy services ladder is defined as "an assessment of the relationship between household income and the types of energy service it receives, not simply its lack of access to energy" (Sovacool, 2011). According to energy ladder approach (Leach, 1992), "households switch to more convenient energy forms as their disposable income increases".

Each step of the energy services ladder relates with a different set of energy use problems with different impact on households. At the lowest level of the ladder, it is a matter of survival, with shortages of fuel wood or lack of essential equipment as for example refrigerator to keep vaccines in a controlled temperature or kerosene to provide light during the storm. However, energy use problems become less painful for the middle and top of the ladder since they have wealth and resources to adapt (Bhide and Monroy, 2011; Sovacool, 2011). Low-income households (including urban poor) mostly prefer to use biomass for cooking and heating. With the increase in income it is observed that electricity and modern energy fuels are used for modern appliances, lighting, and communication but often they do not substitute cooking and heating. It is only in high-income groups that biomass is fully substituted for energy services (Bhide and Monroy, 2011) (Figure 4).

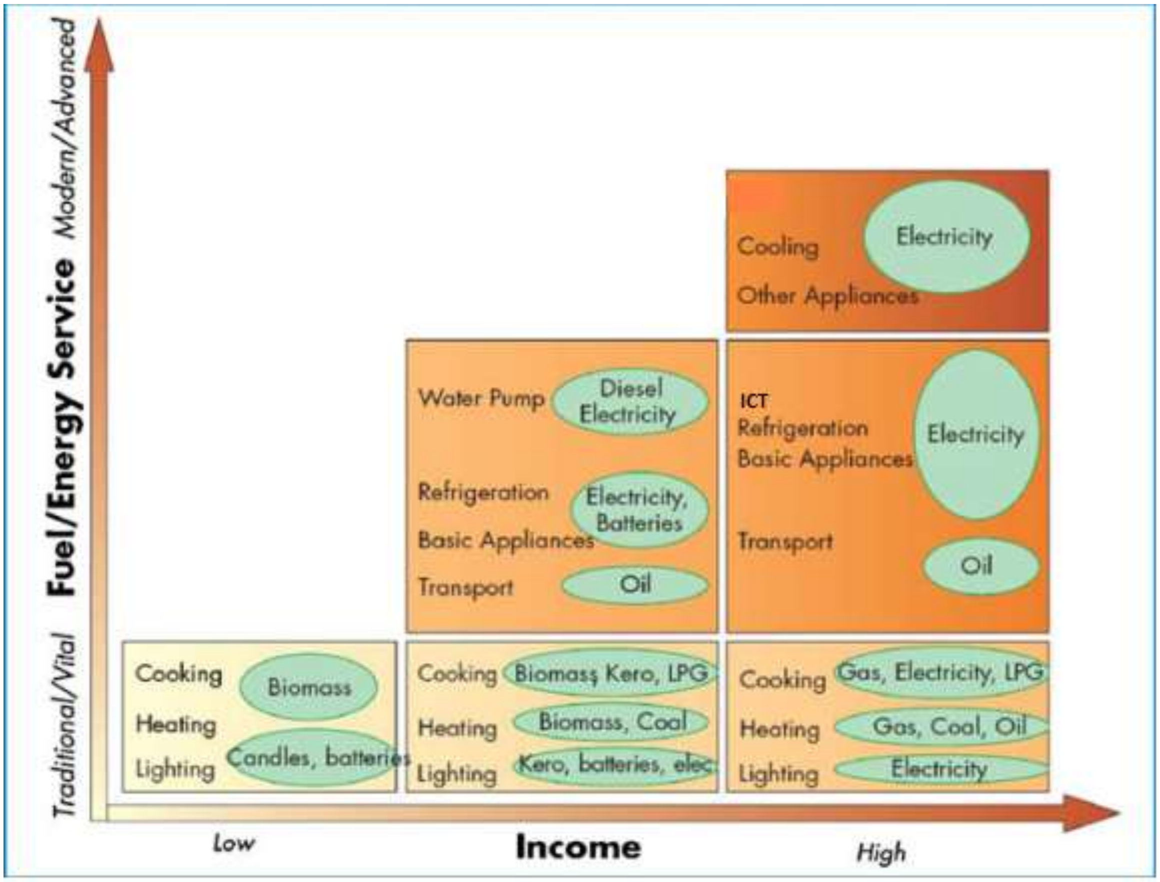

Figure 4: Household fuel transition from energy ladder concept (Source: IEA, 2009)

Provision of modern energy services helps in driving growth by increasing productivity to all income groups. Modern energy services contribute to economic growth by reducing unit costs. Because of the inefficiency of normally used items such as biomass, candles, and kerosene, the slum households often pay higher unit costs for energy (Modi et al, 2006). By using efficient energy carriers and devices, slum households can achieve cost savings that in turn be spent on their development work such as health, education etc.

A study led by Jorgenson et al. (2010) using the sample of less developed countries from 1990 to 2005 highlight that there is a negative relationship between growth in energy consumption and the growth in the percentage of slum population. However, they noted a positive association between growth in energy consumption and growth in overall urban population. This finding reflects the energy under-consumption of slum population which is possibly a sign of unequal urban development. The urban poor does not have proper access to the energy services due to varied reasons. They also tend to pay higher prices for poor quality energy services such as kerosene based lighting and biomass cooking fuel. Slum dwellers are frequently overlooked and bypassed by governments and funding agencies focus on rural populations although they play an important role in the economic growth of a city. However, since slum dwellers live very close to the electricity grid, with relatively low cost a great progress on increasing energy access can be achieved (Nordhaus 2016).

Low-income urban households (including slum dwellers) principal fuels and technologies related to energy services vary considerably compared to urban middle and upper-income households. It is expected that with economic growth, slum dwellers' energy use patterns will change, and they move up in the energy ladder towards middle and eventually high-income groups. Policies and programs focusing low-carbon and efficient energy systems for urban poor are hence critical. A description of urban household energy services is given in table 2. Cooking, lighting (primary energy services) and appliances as well as space heating and cooling (secondary energy services) are most widely used among the urban poor in the developing world (Sovacool, 2011). Although urbanization is believed to reduce dependence on biomass-based fuels, modern cooking fuels such as LPG in towns and cities is not extensive. About 58% urban people in Sub-Saharan Africa and a quarter of people in South Asia are still dependent on biomass resources as their primary fuel for cooking (IEA, 2006). It is considered a sign of decarbonization and is a positive phenomenon where fossil fuels such as LPG replace biomass-based fuels such as wood and dung in the studied regions (Nordhaus 2016). Lighting, television, radio, and telephone are main energy services in low-income households along with cooking and hot water (Dutschke et al. 2006). The predominant force behind the energy use among urban poor is maintaining subsistence. Women and children in such households spend several hours every day cooking and searching for fuel. Globally approximately half of the population uses solid fuels (Rehfuess et al., 2006).

Middle-income urban households use electricity and natural gas as primary fuels and energy carriers. These households use a larger set of energy services such as air conditioners, space heaters, refrigerators, water heaters, washing machines, and other modern appliances (Fridtjof, 2005; Zhang, 2004). High-income urban households use the same energy services but consume more energy. The driving force behind their energy use seems to be conspicuous consumption or social signaling which means signaling their affluence (Sovacool, 2011; Jackson, 2005).

Table 2: Urban household energy services

Household Income group	Primary fuels	Primary technologies	Energy Services	Energy use problems	Driving Force
Low Income (including *slum dwellers*)	*Wood, dung, Kerosene, Charcoal,*	Cookstoves, open fires, candles	Cooking and lighting, infrequent uses of television, radio, and hot water	Fuelwood shortage, high costs of grid access and connection, lack of energy appliances	**Maintaining subsistence**
Middle-income	Electricity, natural gas	Air conditioners, space heaters, refrigerators, water heaters, washing machines, and other modern appliances	Space heating, cooling, hot water, cooking, entertainment, lighting, refrigeration, washing and drying, television, advanced telecommunication	Brief interruptions to electricity, shortages of transportation fuels	Convenience, comfort, and cleanliness
High-income	Electricity, natural gas	Multiple air conditioners, space heaters, refrigerators, water heaters, washing machines, and other advanced appliances	All of the middle-income services plus luxury practices such as swimming in a heated pool, and watching television while cooking	Unanticipated increases in energy prices	Convenience, comfort, cleanliness and conspicuous consumption & social signaling

Adapted from Sovacool (2011) for this research purpose

Here a short description of energy access and usage issues for the popular fuels among slum households is given. It is observed that access and use issues across the regions around a particular fuel remain similar (Dhingra et al. 2008). Cooking food is most important and basic energy service. Kerosene is the main cooking fuel for a majority of slum households both in South Asia and Sub-Saharan Sub-Saharan Africa. Usage of kerosene for cooking with LPG or biomass and/ or charcoal is common in most of the slum households. The price of kerosene is linked with the world crude oil however in some countries it is highly subsidized for poor households such as in India (Dhingra et al. 2008, GNESD 2013).

Households that are unable to afford LPG or kerosene use biomass for cooking. The availability of biomass varies from place to place in a city. Slums on the outskirts of a city have an easier access to biomass than slums located in the city center. Apart from biomass, cow dung cakes, wood scrap etc are also used in some slums. The poorest of the households use only biomass for cooking. This manner of cooking using solid biomass produces toxic indoor air pollution due to incomplete combustion and thus causes a plethora of problems, including fatal upper respiratory illnesses and major contributions to global climate change (GACC 2013). Traditional cookstoves are also low in combustion efficiency, leading to higher cooking times, excessive consumption of biomass and emissions of GHG. Even households that have access to LPG and kerosene cook certain food like Indian bread (*chapatti or roti*) using biomass for the sole reason of taste (Dhingra et al. 2008). Therefore social and cultural preferences and behavior affects the energy use. Multiple fuel use is also common for different cooking tasks as a protection against shortages of modern fuels. Biomass can be purchased on a daily basis and therefore there is no need to pay for any upfront cost which makes it an attractive fuel option for urban poor. Use of solid biomass is also related to the lack of awareness of its detrimental effects of burning in the health and environment (Karekezi et al. 2008).

LPG is mostly used by wealthier slum households which are also distinct by their permanent house structures. One of the main reasons of limited diffusion of LPG is the need to first obtain a proof of address that hinges on having a secure legal status or tenure. In cases when people are eligible to get LPG connection, affordability becomes an issue since many of them are daily-wage workers (Dhingra et al. 2008; Karekezi et al. 2008). These issues restrain in getting LPG connection to urban poor and force them to use fuels such as kerosene, biomass, and charcoal which are procured in small quantities and on a daily basis at an affordable price. It is noteworthy that on a monthly basis the amount spent on cleaner fuels such as LPG or kerosene is fairly comparable than the amount spent on solid biomass. This alone highlights that there is need to make sure slum households have access to cleaner cooking fuels (GNESD 2013, Dhingra et al. 2008).

Going from the kerosene wick or pressure lamps, to the use of incandescent or fluorescent lamps, lighting technologies follow a fairly clear technological progression in performance, efficiency, and cost. Electric lamps are generally classified into — incandescent, ballasts, Compact Fluorescent Lights (CFLs), and Light Emitting Diodes (LEDs). Incandescent lights are the least efficient electric lighting technology and have the highest operating costs. Incandescent lamps are used extensively particularly in the urban poor households as they are inexpensive if the operating cost is not included. A ballast is also called a choke and is needed to operate a fluorescent lamp. The combination of an efficient lamp and electronic ballast can reduce the power consumption with no loss of light (Byrne 2013). LEDs and CFLs are more efficient and last longer, however, they are more expensive than incandescent lamps. LEDs are most expensive among currently available lighting technologies and also most efficient. Slum households can quickly switch to LEDs and CFLs if the government and/or other organizations support are available. At the first sight, the price of the efficient appliances look high, but at current and rising electricity costs, opting for efficient appliances is a wise decision especially to substitute the high usage appliances from slum household context studied in this research as refrigerator, fans, TV, and lightings.

End use energy consumption for a particular appliance depends on the efficiency as well as on the usage pattern. At the same time change in size and features of appliances play important role in determining the end-use energy consumption. Increasing wealth along with decreasing appliance prices drives the growth in appliances ownership. The increase in consumer appliances is creating rapid demand for energy in developing countries. Lights are the first appliance acquired by a slum household when it gets electric service followed by fan, television, and then refrigerator. Refrigerator ownership is presently quite low in developing countries and even lower among slum households. Secondhand refrigerators are also popular as they come cheaply though they are less efficient and their operating costs are high. Sometimes slum households do not have a valid residence proof and they resort to illegal hooking for obtaining electricity. However, there are efforts underway in many countries to connect urban poor with electricity from innovative schemes despite not having secure tenure (Karekezi and Onguru, 2008, GNESD 2013). Lack of affordability is an issue for electricity connection where one time upfront cost and recurring cost of bills become a barrier. When electricity is available, cheaper and hence inefficient appliances are mostly used. Lack of awareness coupled with high upfront cost becomes hindrance for using efficient appliances (GNESD 2013).

Diffusion and adoption of efficient devices therefore are needed to be understood from the lens of sociotechnical transitions, the topic of which is explained in the next section.

2.3 Diffusion and role of technology in society

In order to achieve widespread diffusion and adoption of efficient energy devices, the relevant topic, however, is the spread of efficient technologies at the societal level – the diffusion of innovation, "the process by which an innovation is communicated through certain channels over the members of a social system" (Rogers 2003: 5). Rogers further clarifies that diffusion can be seen as a "special type of communication, in which the messages are concerned with a new idea" (Rogers 2003: 6). It is the newness of the idea that gives the technology its innovation over existing practices, and hence its inherent value, but it is also what can lead to uncertainty and, in turn, unreliable consumer perception of the product. Thus, in Rogers' framework, it is the communication that is meant to mold the users' perception of its value that is most important to the adoption of a new technology. Understanding the dissemination of efficient technologies in slum households in light of the Rogers framework may help in understanding the crucial factors on which successful diffusion may depend.

According to Rogers 2003, potential users of a technology first look at the characteristics of the technology in order to decide whether to use it. Potential users evaluate innovation in terms of technology's: Relative advantage - Is the new technology perceived better than the one it aims to replace?; Compatibility - Is the new technology perceived as being in accordance with the existing values, past experiences and needs of potential adopters?; Simplicity - Is the new technology perceived as simpler to understand and use than the one it aims to replace?; Trialability - Is there an opportunity to experiment with the innovation on a limited basis?; Observability - Are the results of innovation visible to others?

Rogers 2003 further mentions that getting a new technology adopted, even when it has clear advantages, is difficult, therefore the availability of above five variables of innovation speed up diffusion of new technology to the target social groups. Relatively few efforts have been devoted to understand the diffusion of efficient technologies among urban poor. Also, there seems to be little information available about the factors that have been most important for the successful diffusion of efficient energy technologies in practice. Therefore in order to be more impactful, the efficient energy technology has to be used by people in a manner that support their desires and needs under the constraints of culture, institutions and economics. Therefore the solution must be developed in concert with wider context of social, cultural and economic factors of its users. Designing and implementing dissemination strategies that leads to successful adoption or sustained use of these technologies are hence important. Careful design and implementation of efficient technology dissemination from the beginning would increase the likelihood of successful diffusion.

To find potential solutions in the diffusion of efficient technologies we also need to focus on the growing role of social innovation in addressing energy efficiency and energy access. Social innovation projects are developed by social entrepreneurs with innovative models that break away from traditional practices in order to adapt to the users' needs. Innovative business models as a result of social innovation that take care of users need as described above by Rogers (2003) may have more potential to succeed in the penetration of efficient energy technologies among urban poor households. I provide here one such best practice from the Entrepreneurs du Monde in how social innovation in the energy for slum communities in Manila enables them to reach out to communities otherwise lacking electrification.

In absence of electricity many Manila slums use kerosene lamps and candles which are harmful and dangerous. Entrepreneurs du Monde partnered with Total to launch ATE Co. project in order to provide quality lighting system to them. ATE Co. has come up with a rental service of LED kits that provide up to 24 hours of lighting which are recharged and delivered for only 15 pesos (0.3 USD) per day. Several micro-entrepreneurs coming from the slums, trained and supported by the ATE Co. team deliver these services hence creating employment to the communities as well. The company has developed Pay-as-you-Go model which is fully suited to the poorest slum households. Apart from the financial service itself, the team provides a full service such as installing a product, training the family to use, payment collection and maintaining the kits. There are several other such companies that are working in the developing and low income countries in SSA and SA along the social innovation with unique business model fully adapted to the local needs of slum households[1].

Whereas it is important to understand the process of diffusion and adoption from the sociotechnical transitions lens at the same time, urban policies or more specifically slum policies

[1] http://www.entrepreneursdumonde.org/en/nos-actions/nos-partenaires-locaux/ateco/

and programs play an important role in facilitating clean and sustainable energy provision among slum households which are described in detail in the next section.

2.4 Slum improvement policies and programs till date from a housing perspective

According to the United Nations (2006) – “As the developing world becomes more urban and as the locus of poverty shifts to cities, the battle to achieve the Millennium Development Goals (MDGs) will have to be waged in the world's slums”. The massive urban transformation will create a great amount of demand for affordable housing needed for urban poor. It was estimated that US$300 billion would be needed over a 15 year period, or US$25 billion per year to fulfill the requirements of the projected slum growth (UN-Habitat and World Bank, 2005). There have been significant efforts in policy responses to tackle the slum challenge in the past 35 years. There were estimated 100,000 dwellings built in between the 1950s to mid-1970s by developing countries as a result of their efforts to meet the housing crisis through the public housing (UN-HABITAT, 2003).

Urbanization helps in reducing poverty by generating new opportunities, raising incomes and by increasing the number of livelihood options. Conversely on the flip side, when accompanied by weak economic growth and ineffective or absent distributive policies, the outcome of urbanization is increasing the concentration of poor people rather than poverty reduction. Academic community and policy makers have acknowledged the acute need and associated challenges to provide quality energy services to urban poor in sustainable ways (GNESD, 2008). Although energy ties all the developmental aspects (health, education, sanitation etc.), it is not sufficiently emphasized in slum development. There is a need to integrate sustainable energy provision into the slum development programs and strategies. Therefore, this section is devoted first to finding out the programs that are effective in tackling slum problems and then exploring if sustainable energy provision could be integrated into it.

The way informality as manifested by slums has been viewed, narrated, and tackled has changed considerably over time. There has been a range of viewpoints, regarding slums as illegal and eviction as a remedy to positioning slums as a legitimate process that contributes to city building (Boano & Astolfo, 2016). Slum improvement policies and resulting programs are described starting from the mid-1970s when concerted efforts for slum improvement begin to take shape. Negligence and eviction were the norm as an approach to tackle the slums problem prior to 1970s preceded by assisted self-help, and finally enabling approaches in the form of slum upgrading. There is a need to integrate sustainability components such as efficient energy provision in slum upgrading. The section ends with a commentary on slums future keeping in view of the existing trends and best practices if they become the norm.

For the long period, slums have been associated with undesirable and frightening living conditions, and remained outside of the interests of architects, policy makers, and urbanists (Boano & Astolfo, 2016). The negligence approach opines the view that slums are illegal and temporary phenomena and which would be solved itself by economic development. Although this approach was widespread until the 1970s, it is still present in many cities in the developing countries. The approach can be seen in planning documents and plans which shows slums as empty areas without built structures (UN-Habitat 2003b). In the eviction approach governments, without any negotiation or alternative solution, opt for selective or mass removal of slum households. This approach has been recognized by the United Nations as a gross violation of human rights (UN Millennium Project, 2005); however few instances are still seen even today. The eviction, in turns, increases poverty as the destruction of capital assets, loss of sources of income, and links of community cooperation is broken (Arcila 2008). Negative views on slums were widespread that led to slum clearance and relocation as the common response. Governments were unable to provide alternative housing for the majority of migrants/evictees which forced them to build new informal settlements (slums) to the urban fringes.

Assisted self-help became the main policy approach to delivering housing from the mid-1970s onwards primarily based on the notion of incremental housing (UN-HABITAT, 2003). Incremental housing concept recognizes that often urban poor start with an improvised basic dwelling with small savings only when and if it is available. Over a period of time, however, this most basic housing is transformed into a good quality, comparable to urban middle-income standard home (Gattoni, 2009). Sites and services program originated from the concept of incremental housing which gave provision of empty land with basic services for residents to build their own houses. Sites and services scheme prescribed to clear the centrally located slums and relocate them to newly plots often located outside of the existing urban areas. The policy was mainly driven by the tenets of affordability and cost recovery (van der Linden, 1986). The program recognized and capitalized on the ability of low-income residents to organize informal resources. In general, the implementation of sites and services scheme could not address the slum management issues and failed as there was no provision made for preventing or even reducing the future expansion of slums. The new strategies had to be introduced without relocating or clearance of existing slums as well as taking into account of the future slum growth (Sietchiping, 2005, UN HABITAT 2003).

During the 1980s, the slum management policies highlighted the improvement of infrastructure and services in the form of slum upgrading projects as 'enabling approach' within the slums (Banes et al., 2000). Slum upgrading came as an alternative to the sites and services and regarded as best practice (UN Habitat, 2003). In this approach, governments act as 'facilitators' rather than 'providers' (Pugh, 2001). Slum Upgrading, according to the Cities Alliance (1999) "consists of physical, social, economic, organizational and environmental improvements undertaken cooperatively and locally among citizens, community groups, businesses and local authorities". Generally, these projects do not include house construction since residents themselves can do this. An important rationale for slum upgrading is that when supported appropriately by governments, local residents can cover about 80 percent of the required resources (UN-HABITAT and World Bank, 2005). Often there is a provision for optional loans for house improvements. Actions generally include the provision of most basic services such as water and sanitation, drainage, roads, footpaths, often accompanied by security with tenure. Slum upgrading essentially leads to poverty alleviation (Cities Alliance, 1999). Since slum dwellers' home are their workplaces and warehouses as well; if their homes and environment are upgraded and secured, that becomes a major contributor to their employment (Cities Alliance, 1999). Therefore slum upgrading enhances their productivity, strengthen their employment and help them move out of poverty.

In the late 1990s slum prevention has become the main strategy by bringing together access to land and tenure security, access to credit, and providing basic infrastructure (Cities Alliance, 1999). Currently, the slum management strategy emphasizes on mobilizing domestic capital and private finance. The main lessons learned so far from slum upgrading activities are: comprehensive, in situ, approaches by combining community mobilization, tenure security, affordable housing finance, and improved municipal finance, access to employment opportunities, low-cost infrastructure, and services based on effective community demand are widely preferred (Habitat for Humanity, 2007).

Although presented as a solution to the slum development, so far slum upgrading has lacked some key aspects that are needed to improve to provide low-cost affordable housing to the urban poor. However, regardless of specific successes, slum upgrading programs also had weaknesses and in general failed to meet their expectations. The programs were mainly financed by foreign agencies and over time the support was diminished. Local governments could not sustain the financial cost of upgrading (Sietchiping, 2005). As a result, many programs were not sustained or maintained. According to Amis (2001), slum upgrading program in Indian cities had no contribution to poverty reduction which the program originally aimed to achieve. Often slum upgrading programs either did not secure tenure or integrate with income generating activities (Sietchiping, 2005). If land ownership is unclear, it is difficult to get residents to pay for the public services or to improve their dwellings (Werlin, 1999). Due to the insecurity of tenure, slum dwellers did not undertake housing improvements or upgrade their individual dwellings (Werlin, 1999). Tenure insecurity impedes any attempts to upgrade housing conditions for the urban poor and weaken long-term planning (Almansi, 2009). Once informal occupation rights became full private property rights, this would eventually lead to the reduction of urban poverty as residents started to gain the formal market economy benefits (Almansi, 2009). With this reason, security of land tenure should be a precondition for undertaking an upgrading project (Werlin, 1999). Apart from this, upgrading programs only reached to a small portion of slums and never developed into an ambitious project to provide shelter on a city level (Sietchiping, 2005). Furthermore, the upgrading did not take into account of emerging slums as well as did not provide a proactive approach towards the creation of future slums (Sietchiping, 2005).

It has been observed with many slum upgrading projects that most often cost recovery for infrastructure is a big challenge (Habitat for Humanity, 2007). Replication of successful projects at a wider scale has hardly ever achieved mainly because of systemic constraints in accessing capital at scale fueled by complex administrative procedures and inflexible professionals (Habitat for Humanity, 2007). Also, rigorous building standards and physical planning requirements do not give freedom for community's ingenuity to take place which results in upgrading efforts making unaffordable (Werlin, 1999).

Most of the countries in Sub-Saharan Africa and South Asia have policies that, at least theoretically, encourage access to modern energy sources, but they have disjointed measures such as subsidies and lifeline tariffs to promote these goals. However, none of the countries in both the regions have developed comprehensive policies to promote clean and sustainable energy access with a special focus on the urban poor (GNESD, 2013). Therefore city planners and policy makers need to explore options to make the transition and upgrade of slums as energy efficient as possible especially in the context of rapid urbanization and climate change.

Construction of houses and other buildings and infrastructure put an adverse impact on the earth's environment. Proposals have been made to reduce this adverse impact with planning, designing, constructing and maintaining of residential units under the framework of sustainable housing (Ofori, 2007). Housing is a fundamental human need, and most governments are committed that their citizens have an adequate and affordable standard of housing (Ofori, 2007). UN-Habitat's Global Strategy for Shelter (1998) defines adequacy as: "Adequate shelter means ... adequate privacy, adequate space, adequate security, adequate lighting and ventilation, adequate basic infrastructure and adequate location with regard to work and basic facilities - all at a reasonable cost." However, there are currently gaps between needs and provisions of adequate housing in most of the countries and especially in the developing world (Ofori, 2007). Large resources will be required if we are to fulfill this gap accompanied with substantial environmental impacts with such levels of activity.

Although the energy use requirements of upgrading slums for building operations is small, the initial investment in the form of embodied energy in constructing new dwellings may present obstacles in especially developing country cities. Upgrading slums would involve more than dwellings on par with average urban residential units. It would also mean paved streets, basic services like water, sewer, and garbage collection. As they are integrated into the fabric of the city, they can also contribute more to the economic development of the city. Integrating sustainability components in slum upgrading means the use of construction elements that reduce the environmental impact of construction, minimize the maintenance burden, and improve the quality of life. The prime criteria for ensuring sustainability could be affordability, technical feasibility, and low environmental impact. Improvement of slum upgrading practices is important so that the increasing numbers of slum dwellers do not put further pressure on the earth's climate system and become a part of clean and energy efficient system as their income grows.

Urbanization will continue to transform populations, places, and the built environment through the first half of the 21st century. Reducing energy use and GHG emissions from the use of efficient appliances by urban poor are critical to meet the climate goals. The large range of potential future patterns of urban development in most of the developing world but especially in sub-Saharan Africa and South Asia, indicate that these regions can gain a lot simply by encouraging energy-saving cooking and appliances. They are also well-positioned to implement the most advanced energy-saving technologies as they are yet to construct the bulk of their building stock. Improving the urban fabric by upgrading slums will extend the benefits of a compact, energy-efficient built environment to slum dwellers and provide a more inclusive improvement in quality-of-life for all urban residents. Successful blending of energy-efficient urbanization strategies with improving the livelihoods of urban residents matter even more for emerging mega-urban regions in the developing world where hundreds of millions of people and infrastructure worth billions of USD will agglomerate.

The futures of slums are envisioned keeping in view of prevalent trends and best practices if they become the norm. The future of slums can be projected in two entirely different variants: slums of hope, and slums of despair. Based on the prevalent trends, despite some successes which could be termed as 'best practices' in formulating slum policies, slums have continued growing in the urban regions of the developing world (Sietchiping, 2005). The available literature suggests that slum policies and programs so far have not served the poor as the main beneficiaries; instead, people from higher income groups have taken over the improved dwellings designed for the target population (Jacobsen et al., 2002). The result that is observed is, in fact, the reverse – fractional, undirected or unrealistic policies that either impractical or benefits only those in power (UN-HABITAT, 2003). Therefore, failure in tackling the slum problem so far indicate that fractional slum policies and programs, which aim to address one or only a few aspects of slum proliferation could even worsen the existence and expansion of slums. The need of the hour is to focus on a more comprehensive approach that will integrate factors of emergence and growth of slums and at the same time cooperate with different stakeholders responsible for addressing slum problem (Sietchiping, 2005). The most striking outcome of past and existing slum policies and strategies are their short-sightedness with respect to housing needs in urban regions (Brennan, 1993; Jenkins, 2001). Most of the time urban authorities do not understand the social and spatial scope of slums and hence end up with solutions that do not address the slum problem (Brennan, 1993; Jenkins, 2001). No matter how depressing slums look; living in slums has made slum dwellers life better off (Eaves, 2007). Almost all slum residents live there by choice which means they themselves think they are better off. The city provides them better economic prospects. The benefits they get can be several times higher than income from rain-fed agriculture (Eaves, 2007).

This urban transformation is so profound that cities are unable to keep up with the population growth. Even when cities provide economic opportunities, life in slums is extremely unsafe (Eaves, 2007). According to the UN-HABITAT report (2003), slum children in Sub-Saharan Africa (SSA) are more prone to die from water-borne and respiratory diseases than their rural children. The report further mentions than women living in slums in SSA have more chances to contract HIV than women from their rural counterparts. Slum children's are less likely to be enrolled in primary education than their urban counterparts. The world's megacities are on the rise but planning and building are not keeping with pace. Slums are primarily being ignored by many governments at their own peril (Eaves, 2007) which could lead to the state of 'slums of despair' in future; a future that we should avoid by all means. Irrespective of these dismal figures, the lure of cities as a provider of better life persists. The world population is estimated to grow at an annual rate of 1.78% until 2030, at the same time rural population reduces in size (Eaves, 2007). Brand (2010) calls squatter cities as 'unexpectedly green', and suggests that we need to seize the opportunity that is offered by urbanization by further greening the growing cities. Slums contain maximum density – roughly a million people per square mile live in the slums of Mumbai, India, and they have minimal energy and material use than their city counterparts (Brand, 2010). Providing the same energy and material use to all the people in cities would require vast infrastructural stresses to energy and food supply. A huge number of people will be climbing the energy ladder from use of biomass to electricity and diesel use (Brand, 2010). Therefore Brand (2010) calls that it is in humanity's biggest interest to provide low energy affordable housing to the urban poor while improving the quality of life as they transition to the energy ladder by not causing much harm to the environment. Governments need a paradigm shift in attitude by looking at the poor settlements not as part of the problem but as part of the solution and look at the poor, not as beneficiaries but primary actors of their own development, key tenets of slum upgrading and enabling approach (Sheng and Mehta, 2001).

In its Global Report on Human Settlements "The Challenge of the Slums" UN-Habitat states that apart from urbanization, slums are mainly the result of a failure of housing policies, legislations, and delivery systems, along with urban policies (UN Habitat, 2003, p.5). Therefore it is important that appropriate policies and strategies are developed to turn urbanization as a powerful poverty alleviating source rather amplifying.

2.5 Conclusion

Although it is well recognized that clean and affordable energy is necessary to avoid the poverty trap, it is still not fully acknowledged as a basic urban service (Dhingra et al. 2008). Building efficiency criteria at the very beginning of providing access, effective energy supply is reduced significantly, the level and quality of energy services are also improved and cost minimized. This provides a way for increasing number of urban poor to develop without increasing emissions i.e. 'mitigation within a development context' – a low carbon future that also fulfills human desires of a good life (Parnell 2014). Slums are considered as transition stage for many rural migrants who come to cities for a better life. The hypothesis is that with economic growth, slum dwellers energy use patterns will change, and they move up in the energy ladder towards middle and eventually high-income groups. Now, from solid fuel based energy sources, they start depending on mainly electricity and natural gas, both of which currently come from fossil fuels. If policies and programs that focus on low-carbon and efficient energy systems are provided for urban poor, they transition to the sustainable energy system with reduced demand than business as usual. The realization of this energy savings potential and associated cost reduction engenders hope about the future of slum households.

These urban poor need to increase energy use primarily to increase their quality of life. The first goal is to provide them energy so that they can abate the burdens of everyday life and can satisfy everyday needs such as education, health care, and lighting. In order to make the energy system productive - clean, reliable and affordable energy resources must be made available for them for at least two reasons. First, if slum dwellers have access to modern energy services they can turn their underdeveloped economic system into productive one, which generates revenues for them so that it is possible for them to pay for energy. Second, since slum dwellers population is projected to increase in future which translates into a huge demand for energy, efficient energy devices do not increases the level of GHG. Therefore environmental sustainability, energy efficiency, and economic development are secured at the same time. Benefits are obvious: better life standard by economic growth and less pollution resulting in improved health.

Chapter 3. Theoretical Framework

The chapter provides modeling literature review by elaborating various modeling techniques applied to forecast residential energy demand in general as well as from the perspective of developing countries. This is with the objective to understand the type of model most suitable for the present research and also to learn from their shortcomings and advantages. Cities in developing countries are increasing in importance as the global community aims to remain below the 1.5°C emissions level. Therefore a review is also undertaken from developing countries perspectives pertinent to the topic of the dissertation. Towards the end, a rationale is given in order to finally select the modeling technique and a comparative assessment is undertaken of the different relevant model types with regards to the research needs.

3.1 Modeling needs for residential energy consumption

Energy consumption characteristics of the residential sector are complex and inter-connected. Therefore comprehensive models are required to assess the techno-economic impacts of adopting energy efficiency and renewable energy technologies pertaining to the residential sector (Swan and Ugursal, 2009). The rationale to use models is diverse that can span from determining regional or national energy supply to household's change in energy consumption due to a retrofit or addition on technology (ibid). Such kind of modeling helps policy decision-making by quantifying the energy use and forecasting the savings. This can also be useful in supporting policies on energy supply, retrofit and technology incentives, new building code, or demolition and re-construction (ibid).

Residential energy use plays a dominant role in dealing with sustainability issues in developing countries. For example, provision of improved biomass stoves plays an important role in reducing the negative consequences of indoor air pollution (van Ruijven et al., 2011). In modeling slums energy use, it is important to understand and take into account the differences between developing and developed countries as well as slum and non-slum regions of urban areas. The socio-economic factors such as income and household size which are driving residential energy use (McNeil et al., 2008; Pachauri, 2004), are more heterogeneous in developing countries than in developed countries (van Ruijven et al., 2011). Also, the transition from traditional to modern fuels and electrification rates play as key factors in deciding future energy usage in developing countries.

Energy use across developing countries is non-homogenous whereas global energy models which are in use currently are too aggregate to account for this non-homogeneity. Historically, the energy consumption of developing countries has often been lower and hence considered less important than the developed countries (McNeil et al., 2008; van Ruijven et al 2011). However recently developing countries energy use is rapidly increasing which has global climate change consequences as well as global and regional energy settings. Energy systems of developing countries are different from those of developed countries, which ultimately have consequences for energy modeling (Urban et al., 2007). According to Bhattacharya and Timilsina (2009), the main issues relevant to developing countries are poorly reflected in energy models, these are urban-poor divide, use of traditional energy resources and differentiation between commercial and non-commercial energy commodities. There is a need for further development of models to better explore the future of energy systems of developing countries in order to help aid policy formulation in these countries (ibid).

A residential energy use modeling review is given here irrespective of whether they have been used for developed or developing countries in order to identify the modeling technique suitable for the study. A comparison between different modeling techniques is given to summarize the modeling review (Table 3).

Modeling techniques for residential energy consumption can be broadly divided into “top-down” and “bottom-up”. This division is primarily based on the hierarchal position of the data inputs of the housing sector as a whole. Top-down models utilize the estimate of overall residential sector energy use and other relevant variables to attribute the energy use to characteristics of the whole housing sector. In distinction, bottom-up models estimate the energy use of individual or groups of houses and extrapolate this to represent the entire region or country (Swan and Ugursal, 2009). Top-down and bottom-up modeling can be further subdivided into sections, which are shown in the Figure 5.

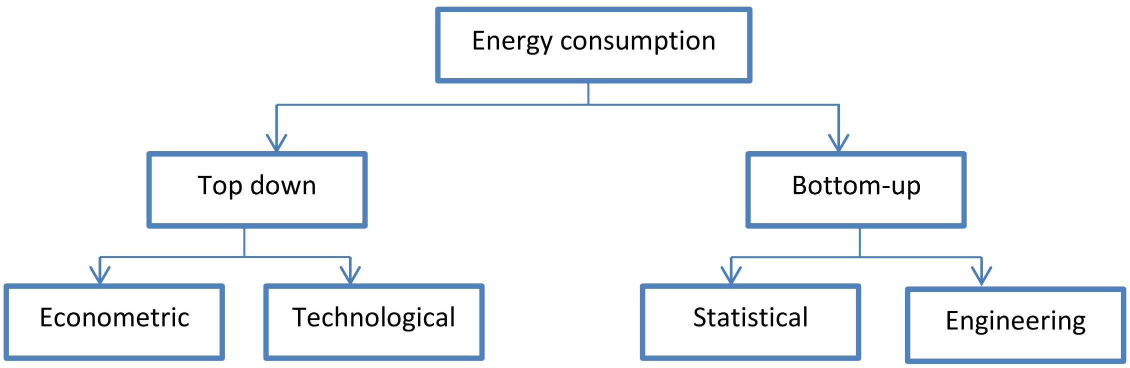

Figure 5: Top-down and bottom-up modeling techniques for estimating the regional or national residential energy consumption (Swan and Ugursal, 2009).

Apart from modeling techniques based on top-down and bottom-up, there are two other types of techniques which have been used for residential energy consumption modeling: hybrid modeling, and Integrated Assessments Modeling (IAM). Hybrid models are essentially derived from the convergence of top-down with bottom-up elements, or vice versa (Swan et al 2013; Hourcade et al., 2006; Urge-Vorsatz and Novikova, 2007). Integrated Assessment Models (IAMs) combine the interactions between economic and biophysical systems into the integrated system (Urge-Vorsatz and Novikova, 2007). A review of literature based on hybrid and IAMs is provided in the subsequent sections.

3.2 Top-down models for residential energy - Overview

Top-down models treat residential sector as an energy sink that does not include technological detail i.e. they do not differentiate energy consumption due to individual end uses (Proença and Aubyn, 2009). Top-down models determine the impact of long-term changes within the residential sector on energy consumption with the objective of determining the supply requirements (Swan and Ugursal, 2009). These models are useful in the assessment of economy-wide policy instruments such as subsidies or carbon taxes but cannot lead to assess the role of technological evolution in order to achieve a low carbon economy (Proença and Aubyn, 2009). The variables which are commonly used in the top-down modeling include macroeconomic indicators (such as GDP, urbanization rate, employment rate and price indices), climatic conditions, dwelling construction/demolition/retrofit rates etc.

There are two types of top-down modeling: Econometric and Technological. Econometric models uses aggregated economic data primarily on price (such as energy and appliances) and income to examine interactions between the energy sector and other sectors of the economy. The main assumption in such models is that the historical trends in the aggregated data comprise adequate information to predict the future (van Beeck, 2003). In technological models, energy consumption is attributed to the broad characteristics of the whole housing stock for example appliance ownership trends (Swan and Ugursal, 2009). However, there are models that use the both of these techniques.

Top-down modeling' strength lies in its use of aggregate data which are easily available, simplicity and reliance on historical values. However, reliance on historical values is also considered as a weakness since top-down models are unable to capture discontinuous progress in technologies (Swan and Ugursal, 2009). Use of historical data is also controversial for economies which are fast changing such as developing economies since past data cannot be used to estimate future trends (Kayode and Nyamapfene, 2011). Additionally, top-down models are unable to identify main areas for improvements for the reduction of energy consumption as they lack the detail regarding energy consumption of individual end-uses (Swan and Ugursal, 2009).

3.3 Bottom-up models for residential energy - Overview

The bottom-up models use input data from a hierarchal level which is less than that of the sector as a whole. Models first estimate energy consumption of individual end uses and then extrapolate the information to represent the region or country based on the representative weight of the modeled sample (Swan and Ugursal, 2009). A strong advantage of bottom-up modeling is its ability to clearly address the effect of resident's behavior and "free energy" gains such as passive solar gains (ibid). Bottom-up models help in identifying the most economic options to achieve carbon reduction targets based on the best available technologies and processes (Rivers and Jaccard, 2005).

Bottom-up models can be divided into Statistical, and Engineering methods. Although there are many statistical modeling techniques available, most of the bottom-up statistical models are based on regression techniques (Kavgic et al, 2010). Statistical Methods (SM) uses historical data and kind of regression analysis that are used to attribute housing energy use to particular end-uses. The statistical methods can be used to estimate the energy use of dwellings representative of the residential stock when the relationship between end uses and energy use has been established (Aydinalp-Koksal and Ugursal, 2008).

Engineering Methods (EM) uses a sample of dwellings representative of the regional or national housing stock and utilize building energy calculation method to estimate the distributed energy use (Aydinalp-Koksal and Ugursal, 2008). Therefore, they require a detailed database representative of the housing stock and apart from this extensive user expertise and long data preparation time. This method includes consumer behavior and other socio-economic variables that can potentially affect residential energy consumption. Engineering based models can be used to evaluate the effect of various scenarios for energy conservation on residential energy use and greenhouse gas emissions (Aydinalp, Ugursal, and Fung, 2000). Bottom-up models based on engineering methods are useful as they provide policy makers with estimates of the effectiveness of policies. They can also be helpful in identifying technological measures that support end-use efficiencies (Kavgic et al, 2010).

3.4 Top-down models for residential energy: Review of existing literature

Top-down models do not need much information about actual consumption processes. These models treat the residential sector as an energy sink and to determine trends by regressing or applying factors that affect consumption (Swan and Ugursal, 2009). Such models mostly depend on similar statistical data and economic theory.

Haas and Schipper (1998) investigated the role of efficiency on total energy demand in the housing sector. They found that energy use of the housing stock is modeled with only a few econometric indicators. They recognized “irreversible improvements in technical efficiency” as the main reason for the moderate growth in energy demand even after plunging the oil prices in 1985. They also observed consumers response by not only reducing energy use due to rising price, but responds by making upgrades to their housing. Therefore we do not observe a perfectly elastic rebound as a result of a reduction in price. The authors developed econometric models for the USA, UK, Japan, Sweden and West Germany. They found nearly zero rebound of energy use after periods of increased price, hinting the typical price elasticity is a diluted average.

Nesbakken (1999) developed two-tier econometric models for Norway that evaluate the choice of system (heating equipment - discrete) and utilization (residential energy use – continuous), testing sensitivity and stability across a range of pricing and income. The author used three years of expenditure surveys and energy use to verify differences along the time element. The author found higher energy price sensitivity for high-income residents than for low-income residents for housing energy use.

Bentzen and Engsted (1999) used simple economic modeling of residential energy use. They tested the below three residential energy use regression models (Swan and Ugursal, 2009):

$$E_{an,t} = c_1 E_{an,t-1} + c_2 I_{disp,t} + c_3 Pc_t$$
$$E_{an,t} = c_1 E_{an,t-1} + c_2 I_{disp,t} + c_3 Pc_t + c_4 HDD_t$$
$$E_{an,t} = c_1 E_{an,t-1} + c_2 I_{disp,t} + c_3 Pc_t + c_4 HDD_t + c_5 Pc_{t-1}$$

Where E is the annual energy use for year t, I is the disposable household income, HDD is heating degree days, Pc is the price of energy, b is a constant, and c are coefficients. They used 36 years of data. They found in all three regression models that long term energy use was strongly affected by income, lagged energy use and lagged pricing.

Zhang (2004) compared Unit Energy Consumption (UEC) to estimate potential changes in the sector's energy consumption by using aggregate national energy values. The author observed the relationship between UEC and Heating Degree-days (HDD) for China, USA, Canada and Japan. The results point that China uses one-fourth whereas Japan uses roughly half the UEC of USA and Canada (Figure 6).

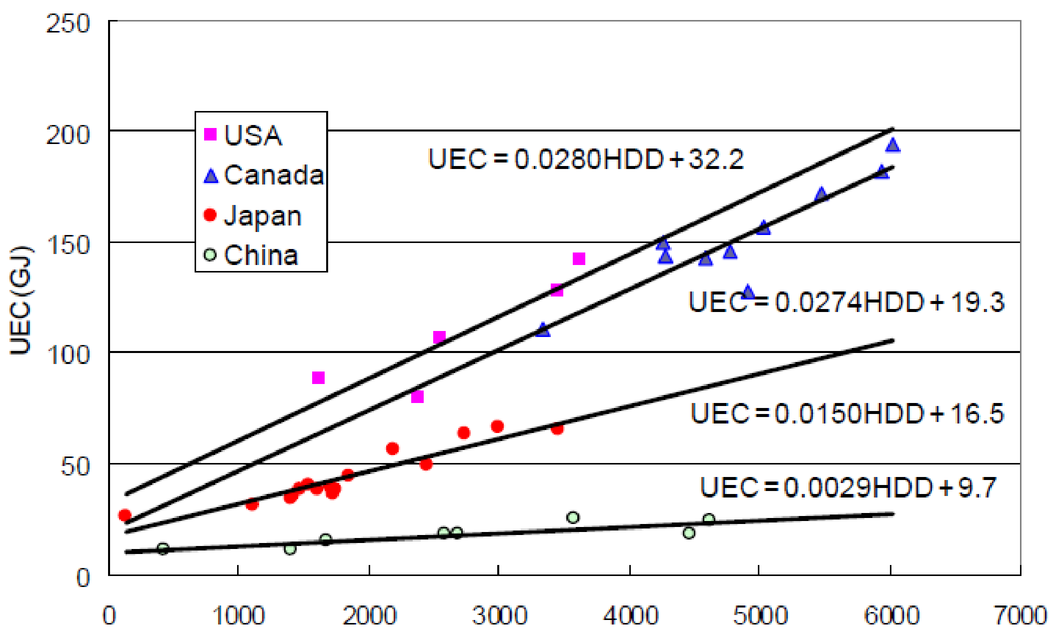

Figure 6: Relationship between national UECs and HDDs

The model presented in the paper identified that the secondary energy use of the housing sector has remained stable although China is growing mainly because of staying away from coal as a fuel. At the same time, UEC of primary energy basis keeps on increasing.

Genetic algorithms (GA) were used by Oztuk et al. (2004) and Canyurt et al. (2005) to estimate the relationship between Turkish building energy consumption and GDP, population, import/export, house production, cement production and house appliance sales.

The national energy modeling system (NEMS, 2010) Residential Sector Demand Module is an econometric energy model of the USA housing stock. The model is used for long-term projections of energy demand and policy analysis. Forecasting of energy demand includes housing stock projection, technology choices, appliance stocks, building shell integrity, distributed generation, and energy consumption. Users can determine the policy impacts which result from the introduction of new technologies, market incentives, and regulatory changes by defining alternative input and parameter assumptions in the module.

Siller et al. (2006) explored the possibility of attaining the twin objectives of reducing the final energy consumption and CO_2 emissions until 2050 from the Swiss housing stock. Their model is based on the effective heated area and census data is used to calculate. They suggest that in order to achieve both targets successful strategy should focus on reducing the specific heat demand in renovation phase and use of carbon-neutral or less carbon intensive heating and hot water system. They also suggest that emission target can be achieved with more flexibility than the energy reduction target.

Broin et al. 2011 estimated future demand for space heating in buildings using top-down analysis in Sweden. They looked at the trends in energy demand for space heating from 1970 to 2005, and forecasted that total demand falls from 52 TWh to 47 TWh by 2050 irrespective of projected upward trends in dwelling and population size. Since price elasticity of energy demand was very low, they conclude that improvements in energy efficiency (by regulatory or technological innovation) are very important.

3.5 Bottom-up models for residential energy: Review of existing literature

The bottom-up approach was developed to identify the contribution of each end use towards the collective energy use of the housing stock. The two different types of bottom-up modeling approaches are used to evaluate energy use in specific end uses. Statistical Methods (SM) uses historical data and kind of regression analysis that are used to attribute housing energy use to particular end-uses. SM models can use macroeconomic data and other regional and national indicators and therefore gain the advantages of the top-down approach. On the other hand Engineering Methods (EM) depends on detailed information of the housing characteristics and end-uses to estimate the energy consumption. As a result, the EM has the ability to model new technologies based on their characteristics only.

3.5.1 Statistical Methods (SM)

Customer energy billing information is primarily used as a data source for modeling. Energy billing and other information are used to regress the energy use as function of dwelling characteristics in SM techniques. A clear advantage of SM techniques is their ability to distinguish the effect of residents' behavior (Aydinalp-Koksal and Ugursal, 2008). Review of SM techniques is further divided into three sections: Regression, Conditional Demand Analysis and Neural Network (NN).

Raffio et al. (2007) provided a four-step method to analyze monthly electricity billing and weather data from multiple households to identify buildings for particular energy conservation retrofits. The method helps in identifying dwellings with the highest energy saving potentials. It also identifies the best type of retrofit, and dwellings energy use performance changes with time. The main advantage of their model is its simplicity that only requires electricity billing data and ability of normalized comparison across multiple dwellings using a sliding scale which is constantly updated from new billing data.

Fung et al. (1999) carried out a comprehensive econometric regression on heating energy consumption, domestic hot water, and appliance energy consumption, the three Canadian housing energy consumption end-uses in order to estimate their long and short term price and income elasticities. They observed fuel price elasticity to be negative and income elasticity to be insignificant for each end-use group.

Tonn and White (1988) developed a regression model with four separate equations of electricity consumption associated with space heating, and appliances and lightings, wood use, and indoor temperature. They carried out a survey that included questions related to attitudes and motivation, and socioeconomic response. Their objective was to find out the ethical considerations or motivation in energy consumption. Their regression equations had the goodness of fit value in the 0.80-0.91 range. Apart from dwelling characteristics, they observed ethical motivations offset economic motivations. Model results also pointed to that central heating houses use more heating for space heating.

The Conditional Demand Analysis (CDA) technique executes regression taking into account end-use appliances. By regressing total residential energy use with owned appliances, the estimated coefficients signify the use level as well as rating. Caves et al. (1987) designed a CDA model for the utility energy consumption of Los Angeles customers and through the use of Bayesian inference, they integrated prior information in an attempt to reduce insignificant coefficients determined by the method.

In this study, they used standard conditional demand model that is based on an equation which essentially states electricity usage as the sum of the usage by each individual appliance.

$$U_{it} = \sum_{j=1}^{M} f_{jt}(Z_{ijt}) D_{ij} + \varepsilon_{it} \qquad t = 1,\ldots,T; \qquad i = 1,\ldots,N$$

Where, $D_{ij}=1$ if customer owns appliance j, otherwise $D_{ij}=0$

Z_{ijt} = variables which determine customer i's utilization of appliance j at time t,

M is the number of appliances,

ε_{it} = random variations

The objective of the CDA is to acquire estimates of the functions $f_{jt}(Z_{ijt})$. This function presents the contribution of appliance j to total usage at time t for provided set of conditions represented by Z_{ijt}.

3.5.2 Engineering Methods (EM)

Engineering Method (EM) is the only method that does not completely depend on any historical energy use information. The method estimate energy use based on end uses characteristics. The EM has the maximum degree of flexibility and capability to model new technologies that do not have historical energy use data. However, the main feature of this method is making assumptions about occupants' energy use behavior which varies to a high degree and that is difficult to determine.

McNeil et al. (2008) estimated the global potential reductions in GHG and associated energy savings by 2030 for energy efficiency improvements associated with building equipment as a result of energy efficiency standards and labeling (EES&L). The model was developed by Lawrence Berkeley National Laboratory (LBNL), USA. The model considers the potential impacts of EES&L for energy consuming equipment. This forecasting model is called BUENAS (Bottom-up Energy Analysis System). BUENAS is the model uses floor space as an activity variable to provide global forecasts of building energy demand. Since all the activity variables are driven directly by macroeconomic variables, it is easy to manipulate the model to examine alternative economic scenarios.

GBPN-3CSEP (Global Building Performance Network – Center for Climate Change and Sustainable Energy Policy) model is a performance based bottom-up modeling approach i.e. treating buildings as entire complex systems and not the sum of their components (Urge-Vorsatz et al., 2012). Key drivers are population, GDP, energy use, buildings stocks, and technological development. Final energy consumption/saving is calculated from total floor area, region, climate zone and building types and their energy intensities based on different building vintages. Building floor area is the main variable for which a model was constructed. Frozen (energy performance remain stable at 2005 levels), moderate (illustrates the lock-in effect- sub-optimal performance level) and deep (best performance) efficiency scenarios are constructed.

Kadian et al. (2007) modeled the total energy use and associated emissions from the residential sector of Delhi, India by using the long-range energy alternatives planning (LEAP). They used energy end use equation to integrate the diffusion and use factors of all households extended to individual end-uses. The total of the end use energy consumption acted as input into the LEAP system to include variables as income, population, and houses. Energy uses under different sets of policy and technology options were evaluated. Also, scenarios were generated to observe the pollution reduction obtainable by different options.

Petersdorff et al. (2006) modeled the EU-15 building stock by evaluating five average buildings with eight insulation standards of European Performance Building Directives (EPBD). They used Built Environment Analysis Model (BEAM) developed by Ecofys to estimate the heating demand for three climate regions. The authors included three dwelling types: water terrace, small and large apartment. They generated different scenarios of retrofit, and construction/demolition. The authors also extended the model to include smaller housing types. The study showed that insulation of the existing housing has the main saving potential. Also, CO_2 emissions could be deeply reduced, if smaller buildings are included in the EPBD range.

3.6 Hybrid Models

Although bottom-up models explain technologies in detail, they do not practically represent decision-making and fail to portray potential macroeconomic equilibrium responses (Algehed, Wirsenius, and Jönsson, 2009). Conversely, top-down models represent macroeconomic feedbacks in an equilibrium framework but since they lack technological detail, they cannot assure that their economic projections are supported by a feasible technical system (Algehed, Wirsenius, and Jönsson, 2009; Hourcade et al., 2006). Due to this methodological difference, top-down and bottom-up models often estimate different energy savings and costs, and as a result suggest different policies (Algehed, Wirsenius, and Jönsson, 2009). This methodological difference motivated the search for a hybrid approach that integrates the technological richness of bottom-up models with the microeconomic responsiveness to policies and macroeconomic feedbacks of top-down models (Algehed, Wirsenius, and Jönsson, 2009). Such kinds of integrated modeling often focus inclusion of macroeconomic feedbacks into a bottom-up modeling and/or technological detail into a top-down framework (Algehed, Wirsenius, and Jönsson, 2009). Hybrid models are able to deliver the detailed information on and understanding of the sectoral impacts, whereas also providing information on the socio-economic impacts of the proposed interventions.

Hourcade et al. (2006) provide a combination of top-down and bottom-up division and an illustration of the three dimensions differentiating top-down and bottom-up models (Fig 7). The figure shows that there is a need for a better model that excels on all three requirements, indicated by the “ideal” model and frequently called hybrid model approach. The result of this hybrid model approach combines technological richness, microeconomic responsiveness and macroeconomic feedback which benefits from the advantages of top-down and bottom-up modeling knowledge (Hourcade et al., 2006). Some original top-down or bottom-up models can progress toward a hybridized approach and therefore this hybridization approach can take different forms.

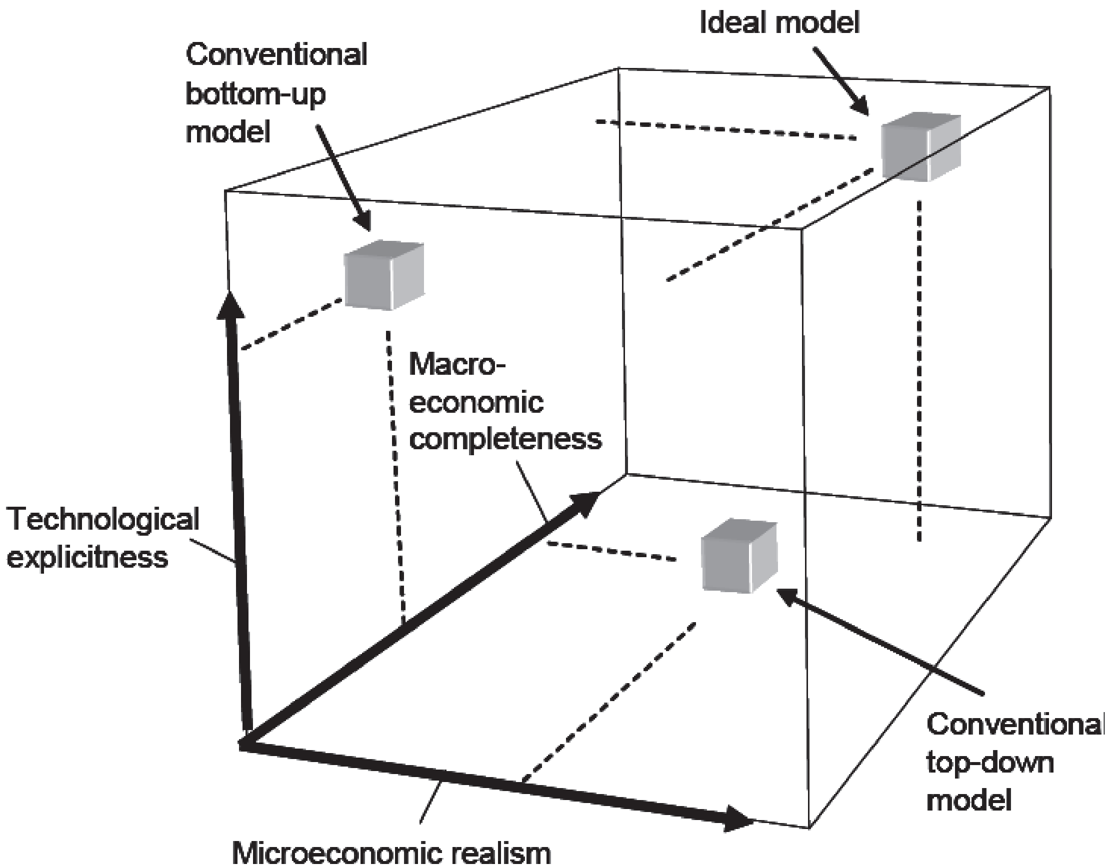

Figure 7: Illustration of top-down and bottom-up modeling approaches' strengths and weaknesses and need for a hybrid (ideal) modeling approach (Hourcade et al., 2006)

Bosetti et al., (2006) presented a hybrid model called World Induced Technical Change Hybrid (WITCH) with the objective of bridging the gap among modeling classes. WITCH is primarily a top-down optimal growth model but energy input specification follows the essence of a bottom-up model. WITCH is a hybrid model in the sense that the economy contains the energy sector. This way capital and resources for energy system are allocated optimally regarding the whole economy. The model takes care of technological progress through learning curves that affect prices and through research and development investments. Apart from this the model also covers the main economic interrelationships between geographic regions and able to analyze the optimal economic and environment policies in regions of the globe.

MARKAL (MARKet ALlocation) is an energy and environmental planning family of models developed in early 1980's by International Energy Agency's (IEA) Energy Technology Systems Analysis Programme (ETSAP). In the start, the model was designed as a linear programming application primarily dealing with integrated assessment of energy systems. Later it was followed up by a non-linear programming framework which integrates bottom-up technologically explicit model with the top-down macroeconomic elements. Recently the MARKAL family of models was enlarged to model material flows, to utilize stochastic programming for addressing uncertainties, and mixed integer programming to model endogenous technology learning and to model multiple regions (Seebregts, Goldstein, and Smekens). MARKAL family of the model represents both the energy demand and supply side of the energy system. MARKAL presents sufficient detail both on energy producing and consuming technologies. It also increases understanding of the relationship between the macroeconomy and energy use (Seebregts, Goldstein, and Smekens, 2002).

3.7 Integrated Assessment Models (IAMs)

Integrated Assessment Models (IAMs) are defined by Rong et al (2007) as – "any model which combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control". Weyant, et. al. (1996) defines IAMs in even broader terms as – "any model which draws on knowledge from research in multiple disciplines". Integrated Assessment Models (IAMs) have been mostly used to clarify the relationships between the fundamental socioeconomic, technological, and other drivers of greenhouse gas emissions and total changes in the global climate. So far IAMs have mostly focused on the supply side of the energy sector whereas treating the demand side for energy in quite aggregate manner.

Rong et al. (2007) presented an approach to comprehend the long term development of the United States (U.S.) building sector by creating a service based buildings module which was integrated through year 2095 for regional and global Integrated Assessment Model (IAM), the Object-oriented Energy, Climate, and Technology Systems (ObjECTS) MiniCAM. There is an upward pressure on building energy demand due to various reasons in the modeling scenarios such as increasing U.S. population and a strong trend towards greater floor space per capita as well as increasing demand for a number of services associated mostly with appliances, office equipment, and information technology. Further, these increasing trends pose a challenge for energy efficiency. The model forecast a 40 percent increase in energy demands regardless of significant efficiency gains. The model also predicts an increasing electrification of the building sector mainly attributed to a bigger increase in the price of fuel oil and natural gas compared to electricity.

The Targets IMage Energy Regional simulation model (TIMER) was developed and used in close connection with the Integrated Model to Assess the Global Environment (IMAGE) 2.2 (De Vries et al., 2001). The integrated system dynamics TIMER model simulates the global energy system at an intermediate level of aggregation based on 17 world regions. The primary purpose of the model is to examine the long-term dynamics of energy saving and the shift to renewable fuels within an integrated modeling framework. The model also looks into long-term trends for energy-related GHG. Price-oriented fuel and technology substitution processes, cost reduction as a result of 'learning by doing', resource exhaustion as a function of long-term supply cost curves and fuel trade are major components of the inbuilt sub-models.

Table 3: Summary of modeling methods with selected examples

		Model features/assumptions/key drivers	Methodology	Selected main findings and implications
Top-down approach	**Haas and Schipper (1998)**	To find out the role of efficiency on total energy demand of the housing sector	Estimation of price and income elasticities by dynamic constant elasticity function	To increase house efficiency by introducing new 'standards'
	Nesbakken (1999)	To see the effect of energy pricing on energy consumption	Two tier econometric models for Norway to evaluate the choice of system and utilization, testing sensitivity, and stability across a range of pricing and income.	Higher energy price sensitivity for high-income residents than for low-income residents for housing energy use. High-income residents are more sensitive to energy price than low-income residents.
	Bentzen and Engsted (1999)	Simple economic modeling of residential energy use.	Testing of the residential energy use regression models.	Long term energy use was strongly affected by income, lagged energy use and lagged pricing.
	Zhang (2004)	To observe the relationship between UEC and Heating Degree-days (HDD) for China, USA, Canada and Japan	Comparison of Unit Energy Consumption (UEC) to estimate potential changes in the energy consumption by using aggregate national energy values	China uses one-fourth whereas Japan uses roughly half the UEC of USA and Canada. Secondary energy use of the housing sector has remained stable.
Bottom-up – Statistical	**Raffio et al. (2007)**	Identify buildings for particular	Use of electricity billing data and normalized	Identified dwellings with the highest energy saving potentials.

approach		energy conservation retrofits by using monthly electricity billing and weather data from multiple households	comparison across multiple dwellings using a sliding scale	Dwellings energy use performance changes with time.
	Fung et al. (1999)	To estimate Canadian housing energy consumption end uses' long and short term price and income elasticities	Comprehensive econometric regression on heating energy, domestic hot water and appliance energy consumption	Negative fuel price elasticity and insignificant income elasticity for each end use group
	Tonn and White (1988)	Role of ethical considerations or motivation in energy consumption	To develop a regression model with four separate equations of electricity consumption associated with space heating, and appliances and lightings, wood use, and indoor temperature	Goodness of fit (R^2) value in the 0.80-0.91 range Ethical motivations offset economic motivations Central heating houses use more heating for space heating
Bottom-up – Engineering approach	**McNeil et al. (2008) – BUENAS**	Evaluation of energy efficiency standards and labeling (EES&L) programs worldwide	The model uses floor space as an activity variable to provide global forecasts of building energy demand	Estimated the global potential reductions in GHG and associated energy savings by 2030 for energy efficiency improvements associated with building equipment as a result of EES&L

		Key drivers are macroeconomic variables such as GDP, building stock, urbanization and population		
	GBPN-3CSEP (Urge-Vorsatz et al., 2012)	Performance-based modeling approach i.e. buildings as entire complex systems and not the sum of their components. Key drivers are population, GDP, energy use, buildings stocks and technological development.	Frozen (energy performance remains stable at 2005 levels), moderate (illustrates the lock-in effect- sub-optimal performance level) and deep (best performance) efficiency scenarios are constructed.	Final energy consumption/saving is calculated from total floor area, region, climate zone and building types and their energy intensities based on different building vintages
	Kadian et al. (2007)	Modeled the total energy use and associated emissions from the residential sector of Delhi, India Key drivers are income, population, and houses	Used long range energy alternatives planning (LEAP) as a modeling device	Energy uses under different sets of policy and technology options were evaluated. Scenarios were generated to observe the pollution reduction obtainable by different options.

	Petersdorff et al. (2006)	Modeled the EU-15 building stock by evaluating five average buildings with eight insulation standards of European Performance Building Directives (EPBD)	Used Built Environment Analysis Model (BEAM) developed by Ecofys to estimate the heating demand	Insulation of the existing housing has the main saving potential. Smaller buildings should be included in the EPBD range to deeply reduce CO_2 emissions.
Hybrid approach	**Bosetti et al., (2006) – WITCH**	Primarily a top-down optimal growth model but energy input specification follows the essence of a bottom-up model	Technological progress is accounted through learning curves that affect prices and through research and development investments	Covers the main economic interrelationships between geographic regions and able to analyze global optimal economic and environment policies
	MARKAL	bottom-up technologically explicit model with the top-down macroeconomic elements	Provides a linear and non-linear programming framework Represents both the energy demand and supply side of the energy system	Presents sufficient detail both on energy producing and consuming technologies. Increases understanding of the relationship between the macroeconomy and energy use.
Integrated Assessment Modeling approach	**Rong et al. (2007)**	Service based buildings module which was integrated through the year 2095	Regional and global Integrated Assessment Model (IAM)	The model forecast a 40 percent increase in energy demands regardless of significant efficiency gains

	TIMER	Integrated system-dynamics to assess the global environment	Simulates the global energy system at an intermediate level of aggregation based on 17 world regions	Examines the long-term dynamics of energy saving and the shift to renewable fuels within an integrated modeling framework Analyze long-term trends for energy-related GHG

Based on the above deliberations and literature review a general feature of top-down, bottom-up, hybrid, and Integrate Assessment Modeling can be provided:

Top-down modeling is most useful for supply-side analysis and management based on long-term forecasting of energy use demand with the help of historical information. Bottom-up statistical approaches use energy bills and surveys to collect information and estimate the energy demand from end uses by incorporating behavioral aspects. Bottom-up engineering techniques primarily estimate energy consumption of end-uses based on detailed characteristics of houses and these approaches are able to capture the impact of new technologies.

All these modeling approaches are useful under given situations. Top-down modeling is most useful in energy supply forecasting as they account for historical energy consumption. Bottom-up statistical methods account for residents' behavior and major appliances to identify behaviors and end-uses that cause unnecessary quantities of energy use. Bottom-up engineering approaches recognize the impact of new technologies based on housing characteristics (Swan and Ugursal, 2009). Hybrid models provide the richness of both bottom-up and top-down modeling approaches. Integrated Assessment Models (IAMs) have been mostly used to clarify the relationships between the fundamental socioeconomic, technological, and other drivers of greenhouse gas emissions and total changes in the global climate. Based on the modeling review, the framework of the bottom-up modeling approach seems most suitable for the present study and hence will be applied.

3.8 Selecting a modeling tool for the research

Cities in developing countries are going to be important nodal points in terms of energy demand and emissions linked. As of now most of the literature on sustainable energy transition is focused on developed countries context as sources of current emissions. However, it is impossible to avoid impacts of climate change if emission levels of developing country cities reach to the level of developed country cities level. The energy systems and the notions of energy transitions of developing countries are fundamentally different than developed countries (Bhattacharya and Timilsina 2009). The urban areas in developing countries host a sizeable portion of urban poor who lack modern energy services and their energy systems often dominated by informal activities. Therefore in these countries, any energy intervention will need to align well with developmental objectives. Cities in these countries are experiencing a rapid rising in energy demand accompanied with income growth and lifestyle change. Due to this reason, the focus should be less about conservation and reduction as applicable in developed countries but rather about using energy more efficiently.

There are several modeling tools available for different purposes, however selecting an appropriate modeling platform must fit into the scope and objectives as well as context of the research. A modeling tool or platform for the research must be suitable for developing country perspectives and associated socio-economic and technical characteristics. The modeling tool also must be able to model energy systems at a regional or global level in contrast to the local level. The complexity and structure of the model chosen ideally should be in coherence with the skills and the time required to build the model. Getting the suitable complexity and structure in the modeling contributes towards the quality of the analysis in terms of relevance – the level of data detail and model complexity which is a good fit to the research context, legitimacy, and credibility (Raubenheimer et al. 2015).

Top-down models may be less suitable for this research; for instance, econometric models target establishing economic relationships between variables and generally used for demand forecasting. Due to their dependence on historical patterns their fitness may be limited for developing countries where economies may be undergoing structural changes (Urban et al. 2007). Top-down models capture aggregate demand and hence they do not allow a detailed characterization of demand; therefore they have less scope to represent the diversity which is a typical feature of the energy sector in developing countries. In comparison, bottom-up models take a disaggregated approach with special regards to end users and technology which enables them a better fit from developing countries context (Urban et al. 2007, Bhattacharya and Timilsina 2009).

Research objectives and questions, data availability, country specifics, and capacity of the modeler all are important factors to select an appropriate model for energy analysis (ESMAP 2012). The research aims to provide evidence-based energy efficient pathways in urban poor context to explore the impacts of different energy interventions. Informal activities are prevalent among urban poor capturing which requires a high dependence on assumptions and/or extrapolations based on available sparse data whose representativeness may not be assured. Modeling is a very data intensive process and the data limitations in the urban poor context in the low income and the developing countries are a real limitation. Therefore model that is easy to use with, flexible with data inputs, and can work with fewer data are suitable for the research analysis. A comparative assessment of the different relevant model types with regards to research needs is given in the table 4.

Stockholm Environment Institute's Long Range Energy Alternatives Planning System (LEAP) software tool is chosen for the analysis because it would be most useful to create regional (multi-country) models in terms of the research objectives and suitable for the many of the considerations of the developing country context. LEAP is a bottom-up simulation accounting tool which also allows easy transfer of data to in and out of the software to other databases for analysis such as Microsoft Excel. LEAP has been used for city, country, regional, and global level energy modeling. LEAP an accounting type model is better suitable to work with developing countries unique features such as urbanization, economic shift, informal sector, and energy poverty among households (Bhattacharya and Timilsina 2009). Ideally LEAP can be used for end-use demand forecasting where the demand side is adequately disaggregated and the numerous drivers such as population are available. Data availability for the study regions (SSA and SA) are challenging, however, this is not used to argue against modeling, instead of modeling process itself instigate the process of identifying and addressing data gaps (Tait et al. 2016).

LEAP can present complex energy analysis in a transparent and most intuitive fashion while it is flexible enough to accommodate a wide array of expertise. LEAP is based on a notion of long-range scenario analysis. Scenarios are self-consistent storylines of how the future energy system might evolve over time under a set of policy conditions within certain socio-economic and demographic setting (Heaps 2017). LEAP helps policy analysts and researchers to create and evaluate different scenarios by comparing their energy uses and greenhouse gas emissions. An important advantage of using LEAP is low data requirements because of its reliance on simple accounting principles and optional aspects of data input. Furthermore, LEAP's flexible and transparent data structure allows the user to create an initial analysis quickly. Later, when more data are available user can add complexity that can provide further details into the research questions (Heaps 2017). Scenarios can be used to ask several 'what if' questions, for example, one that's being asked in the dissertation - what if more energy efficient appliances are introduced in slum households, what would be the energy savings and GHG emission reduction potential.

LEAP has been widely used in the context of urban energy use within developing countries. Below I provide a brief description of the studies with multi-country energy analysis (similar to this study) that have used LEAP as optimal energy analysis modeling tool.

Stockholm Environment Institute prepared a report called - Energy for a Shared Development Agenda: Global Scenarios and Governance Implications (SEI 2012) that developed energy and sustainability scenarios up to 2050 to achieve sustainable energy transformation while remaining within resource use and extremely stringent climate change constraints. The scenarios in the report were developed using LEAP as transparent global energy model. LEAP has also been used under the UNDP Low Emission Capacity Building Programme (LECB) to develop data sets for 22 of the participating developing countries in the LECB. The program aims to strengthen and build capacities of the participating countries by helping them to prepare their low carbon development program activities such as developing greenhouse gas inventory management systems, identifying opportunities for nationally appropriate mitigation actions (NAMA), designing low-emission development strategies (LEDS) etc (UNDP 2011).

LEAP was used as the main tool for mitigation modeling in the project called PROMITHEAS-4: Knowledge Transfer and Research for Mitigation/Adaptation Policy that aims to develop and evaluate climate change mitigation and adaptation policy portfolios and prioritize research needs and gaps for twelve Central and Eastern European emerging economies. LEAP was selected because of its ease of use, transparency, low data requirement and flexibility.

APEC Energy Demand and Supply Outlook 4th Edition, 2009 was developed using LEAP by the South Asian Pacific Energy Research Centre. The outlooks details energy demand and supply forecasts for the 21 member economies of South Asia-Pacific Economic Cooperation. LEAP was used to prepare baseline scenarios for China, India, Brazil, Mexico, South Sub-Saharan Africa, and South Korea for the report – 'Greenhouse Gas mitigation in Developing Countries' (Erickson et al. 2009) that identifies opportunities to support GHG mitigation efforts in these countries by forecasting baseline emission scenarios, collected estimates of mitigation potential, and evaluated challenges and opportunities GHG emission reduction for each country.

The Economics of Climate Change for Central American Countries (ECLAC) prepared a report on the economics of climate change in which LEAP was used to estimate business as usual emissions from Central America's energy sector. LEAP was also used to calculate the benefits of GHG mitigation actions. Many countries have used LEAP to prepare their greenhouse gas mitigation assessments as part of their national communications to the United Nations Framework Convention on Climate Change (UNFCCC). Lawrence Berkeley National

Laboratory's (LBNL) Global Energy Model used LEAP to create a global end use model of energy use.

Table 4: A comparative assessment of the different relevant model types with regards to the research needs

Model	Modeling Type	Description	Applicability to the research
TRACE-Tool for Rapid Assessment of City Energy	Benchmarking tool (may not be considered as a model)	Developed by the Energy Sector Management Assistance Program (ESMAP) The Tool for Rapid Assessment of City Energy (TRACE) is a decision-support system which permits analysts to detect areas of concern and hence identify and harness energy efficiency opportunities. It works by focusing on the underperforming sectors, assesses improvement and cost saving potential, and prioritize actions for energy efficiency improvements.	The tool allows for cross-city comparison of energy performance. However, this dissertation research deals with the country levels energy saving and GHG reduction potential and not at the city level hence this could be a drawback of using TRACE.
HEAT-Harmonized Emissions Analysis Tool	Simulation	This model developed by ICLEI helps to prepare baseline inventories and to track commitments and therefore can be useful to measure and quantify progress against emissions targets. It is hence also useful to guide policy decisions and in the preparation of action plans to local governments in developing countries.	The tool put special emphasis on sustainable energy intervention. Hence its emissions inventory could be used to prioritize areas of action that may be of interest. However, its geographical focus is cities and towns.
Threshold 21 (T21) – System Dynamics Model	Simulation	The focus of the model is poverty minimization strategies by using economic modeling. The model has also been used to monitor Millennium Development Goals (MDGs) and other national development goals.	Poverty reduction is the central theme especially focusing on rural development.
EnergyPLAN	Simulation	Developed by Aalborg University, Denmark EnergyPLAN is an integrated energy system	Designing planning strategies are the focus which aligns well with

		and analysis modeling tool to help design planning strategies for energy. The planning strategies are based on economic analysis of the outcomes of different system investments. The emphasis is put upon energy planning in respect to technology, geography, economic, and institutional conditions.	the topic of the research – sustainable energy transitions.
MESSAGE – Model for Energy Supply Strategy Alternatives and Their General Environmental Impact	Optimization	Developed by International Institute for Applied Systems Analysis (IIASA) MESSAGE is an optimization modeling framework that can model a regional or national energy system for medium to long term planning, policy analysis, and for scenario development.	MESSAGE is an effective optimization tool that is useful to develop energy transition pathways. However, data requirements are vigorous and hence less suitable for the research.
Energy-ENACT Energy Access Tool	Optimization (MESSAGE-Access)	Developed by IIASA in support of the Global Energy Assessment (GEA) the interactive policy analysis tool, ENACT aids in policy advice by visualizing costs and benefits of a policy or a mix of policies for the understanding of the possible development of residential energy access and demand.	The tool is relevant for developing countries perspectives as includes traditional fuels. It also features households with different income levels. However, its major benefit is a visualization tool to support policy advice.
LEAP- Long Range Energy Alternatives Planning System	Bottom-up, accounting, simulation	Developed by Stockholm Environment Institute, LEAP is popular modeling tool for energy policy analysis and mitigation assessment, especially for developing countries. LEAP can model global, regional, national or city level. It is very flexible to be customized according to the project. It also	As outlined above LEAP is used for the analysis as it is the best-suited modeling tool for the research. It is well suited for developing countries context, learning material and support system is

		has an optimization ability (OSeMOSYS – an open source optimization system) that allows for a wider usability.	available, works well with less data availability.
Energy Forecasting Framework and Emissions Consensus Tool (EFFECT)	Spreadsheet-based modeling tool	Developed by the World Bank, EFFECT is an open source modeling tool used for forecasting GHG emissions from a range of development and policy scenarios. It focuses on sectors that are expected to experience rapid growth in emissions and energy uses. It helps in consensus building among various government departments, forecasts energy balances, and amounts of energy generating/consuming assets in a country or sector. It also works well with individual sectors such as residential, transport, industry etc.	EFFECT is a flexible tool that informs government and investment policies in the energy sector. Learning material and support system is available and the tool can also work with fewer data. However capturing energy use scenarios from a socio-economic system such as urban poor is difficult to implement.
Model for Analysis of Energy Demand (MAED)	Bottom-up, Simulation	MEAD helps energy analysts and decision makers to analyse future demand of building sustainable energy systems. It is applicable for the medium and long term analysis at the country or regional level. MEAS reveals the structural changes in energy demand by factoring into social, economic, and technological factors.	MAED provides systematic accounting framework for alternative energy scenarios. It is a good candidate to be used for the research however LEAP is chosen because there is not much support system and learning materials are available for MEAD and also it's provided in Excel workbooks which is less convenient to work with.

3.9 Conclusion

A residential energy use modeling review is presented irrespective of whether they have been used for developed or developing countries in order to identify the modeling technique suitable for the study. The modeling review is based on top down, bottom up, hybrid, and IAMs modeling types. Modeling literature review details the modeling techniques applied in various studies that has analyzed current and future residential energy consumption in general and specifically from the developing countries perspectives. Further, a comparison between different modeling techniques is given to summarize the modeling review.

Based on the modeling literature review, top-down modeling is mostly useful for supply-side analysis and management based on long-term forecasting of energy use demand with the help of historical information. Whereas bottom-up modeling approaches estimate energy consumption using energy bills, surveys, and detailed characteristics of houses and these approaches are able to capture behavioral aspects and the impact of new technologies. Hybrid models provide the richness of both bottom-up and top-down modeling approaches. IAMs have been mostly used to clarify the relationships between the fundamental socioeconomic, technological, and other drivers of GHG and total changes in the global climate.

Towards the end, a rationale is given in order to finally select the modeling technique that is used in the analysis for the dissertation. LEAP, a bottom-up simulation accounting tool which has been used for its versatility and low data needs in various developing countries energy modeling requirements is selected for the analysis. In the next chapter I describe the research design and the methodology using LEAP platform.

Chapter 4. Research Design and Methodology

The chapter describes the research design and the methodology used in the dissertation. First, methodological approach is described in terms of a function of activity level, energy intensity, and efficiency. A simplified structure of the modeling framework for slum households' context is presented and a flowchart of appliances energy savings and CO_2e mitigation calculation is given to describe the modeling process. Next, reference and efficient scenarios and what they entail, slum population growth rate calculation, modeling method and drivers of energy use, and core equations are detailed. Further, end-use diffusion (activity level) methodology, energy intensity calculation for the end-uses, and final energy demand and GHG emissions analysis are provided. The chapter also gives information about data sources those are used for the research.

4.1 Methodological approach adopted in LEAP

The methodological approach adopted in LEAP is straightforward in which slum dwellers household energy demand of different fuels are calculated as the product of an activity level (measuring the level of energy services provided) and an energy intensity divided by efficiency. In its simplest form energy demand for a specific end-use can be defined as a function of activity level, energy intensity and efficiency (Schipper and Meyers, 1992).

$$E = \frac{Activity \times Intensity}{Efficiency}$$

Where activity represents the underlying driving force of energy demand for a particular energy service or end use. Activity refers to the size of the stock, i.e. number of end-use appliances among slum population per country. Intensity represents the amount of energy used per unit of activity. Change in energy sources affects energy intensity, as it happens in cooking and heating end-uses. In the residential sector activity level is parameterized by appliance diffusion which is the average number of a certain type of appliance per households. Energy intensity is driven by usage and capacity of equipment such as size of a refrigerator or hours of use of a television. Intensity includes factors such as behavior aspects and lifestyles as well. Efficiency is the technological performance of the equipment that can be affected by policies.

Levels of activity are first projected forward based on assumptions about economic growth and the way household structure might change (e.g. household size, growth in slum population and energy efficiency) as slum dwellers income increases. The scenarios are driven forward by: slum population growth rate, end use diffusion, and energy intensity. The simplified structure of the modeling framework for slum households is presented in the figure 8 which is adapted from the approach used in Long range Energy Alternatives Planning system (LEAP) for this research. For the objective of energy projections, the end use demands of the slum households are disaggregated into cooking, lighting, and appliances which also include cooling end-use (fan).

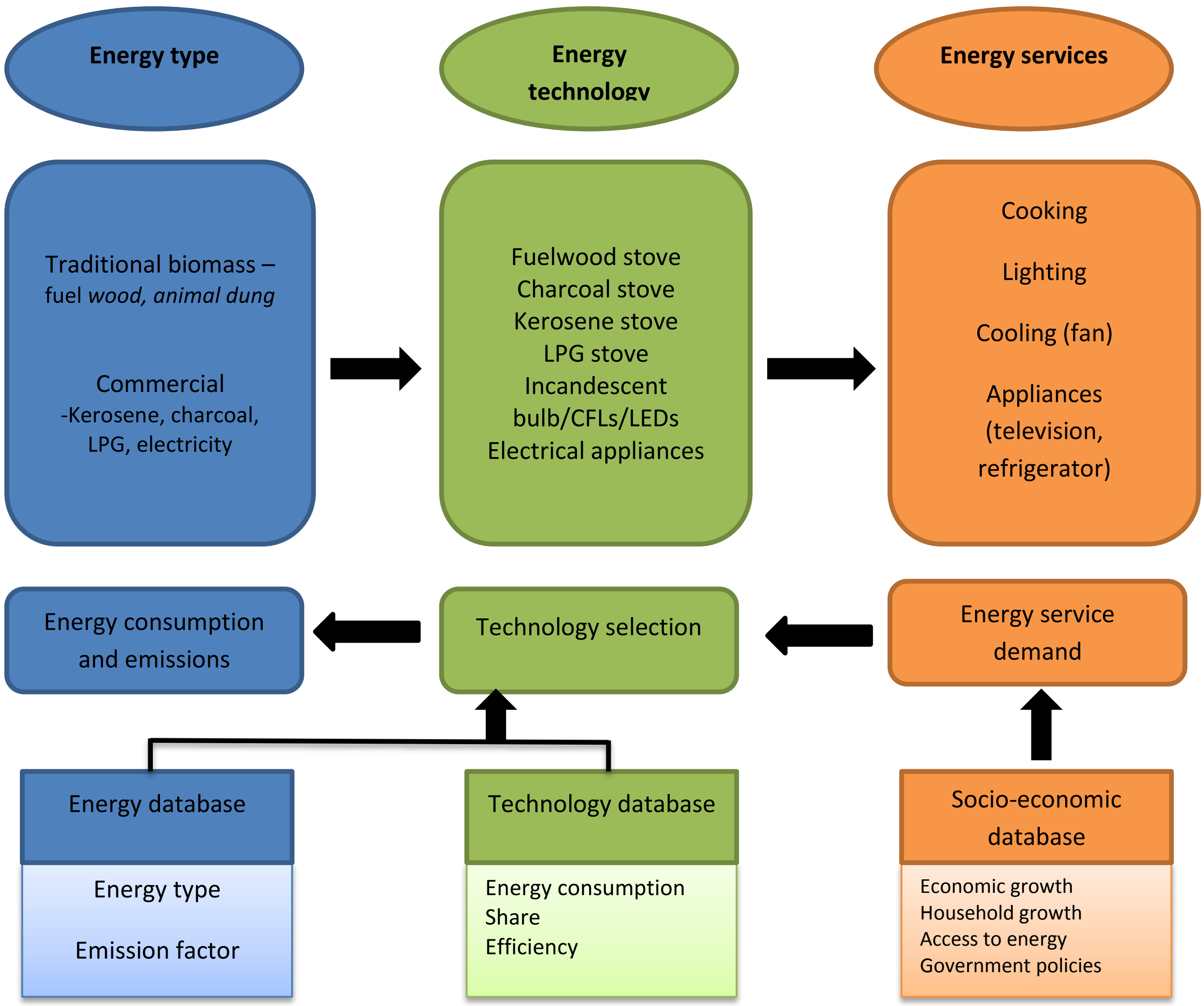

Figure 8: Structure of slum households' energy system modeling framework (adapted from Malla, 2013 for this research purpose)

The energy database that is used in the model comprised of energy types, energy technologies, and energy services. Energy types database consist traditional biomass that is used frequently by slum households such as fuelwood, and commercial types such as kerosene, charcoal, LPG and electricity. Energy technology database comprised of details equivalent to lifetime energy use per end use for each household and includes fuelwood, charcoal, kerosene, and LPG stoves, incandescent bulb, CFLs, LEDs, and electrical appliances. Similarly, the energy service database considers the demand for each service in the slum households and includes cooking, lighting, cooling (fan), and appliances (television, refrigerator). The energy system of slum households is largely divided into energy supply and energy demand. Energy supply includes both primary and secondary energy sources.

Based on the modeling review, the framework of the bottom-up modeling approach is applied to the research. It includes detailed technological information for end-uses; however, it also benefits from socio-demographic data such as urban poor population, household size, and urban poor population growth rates for countries. The approach of the study is largely bottom-up i.e. starting from end-use energy demand and make projections about the whole slum population. LEAP models energy demand at the technology level and forecasts efficiency improvement based on the techno-economic potential of efficient end-use technologies.

The model forecasts energy use by end-uses from 2014 (base year) to 2040. The model projects end-use activity, which is driven by increased ownership of slum households appliances. The total stock of appliances is modeled according to growth rates and target (end year) appliance diffusion since sales projection data are not available for developing countries and particularly for the urban poor segment. Appliance intensity of the stock is then calculated based on estimates of the baseline intensity of the dominant technology in a particular country. The final energy use of the stock is calculated by stock accounting (flow of products into the stock) and marginal intensity. The efficient scenario is created by the assumption of gradual penetration of efficient units relative to the reference scenario (baseline). The stock energy in the efficient scenario gradually becomes lower than that of the reference scenario due to increased diffusion of efficient units. By 2040, the entire stock will be replaced by efficient units in the efficient scenario. The strategy is to first model future energy demand and GHG emissions at the end-use level, and afterward efficiency scenario is built based on efficient appliances available today. Stock accounting tracks diffusion of various products into slum households. Finally, savings are calculated as the difference in energy uses between efficient scenario against reference scenario.

Total stock is multiplied with unit energy consumption to obtain final energy demand. Appliances diffusion is affected by macroeconomic variables as income, electrification, urbanization, and social, cultural and climatic factors. Once the appliance stock of the total number of slum dwellers in a particular country/region is known for the base year, this information is used to project the appliance stock and subsequent energy demand for the reference scenario. Efficiency improvements are assumed based on techno-economic analysis of the stock in order to estimate energy demand for the efficient scenario. Final energy savings from appliance end use are estimated by comparing reference scenario with the efficient scenario. GHG mitigation potential is obtained by accounting for emission factor to respective country/regional energy savings. A flowchart of appliances energy savings and CO_2e mitigation calculation is given below (Figure 9).

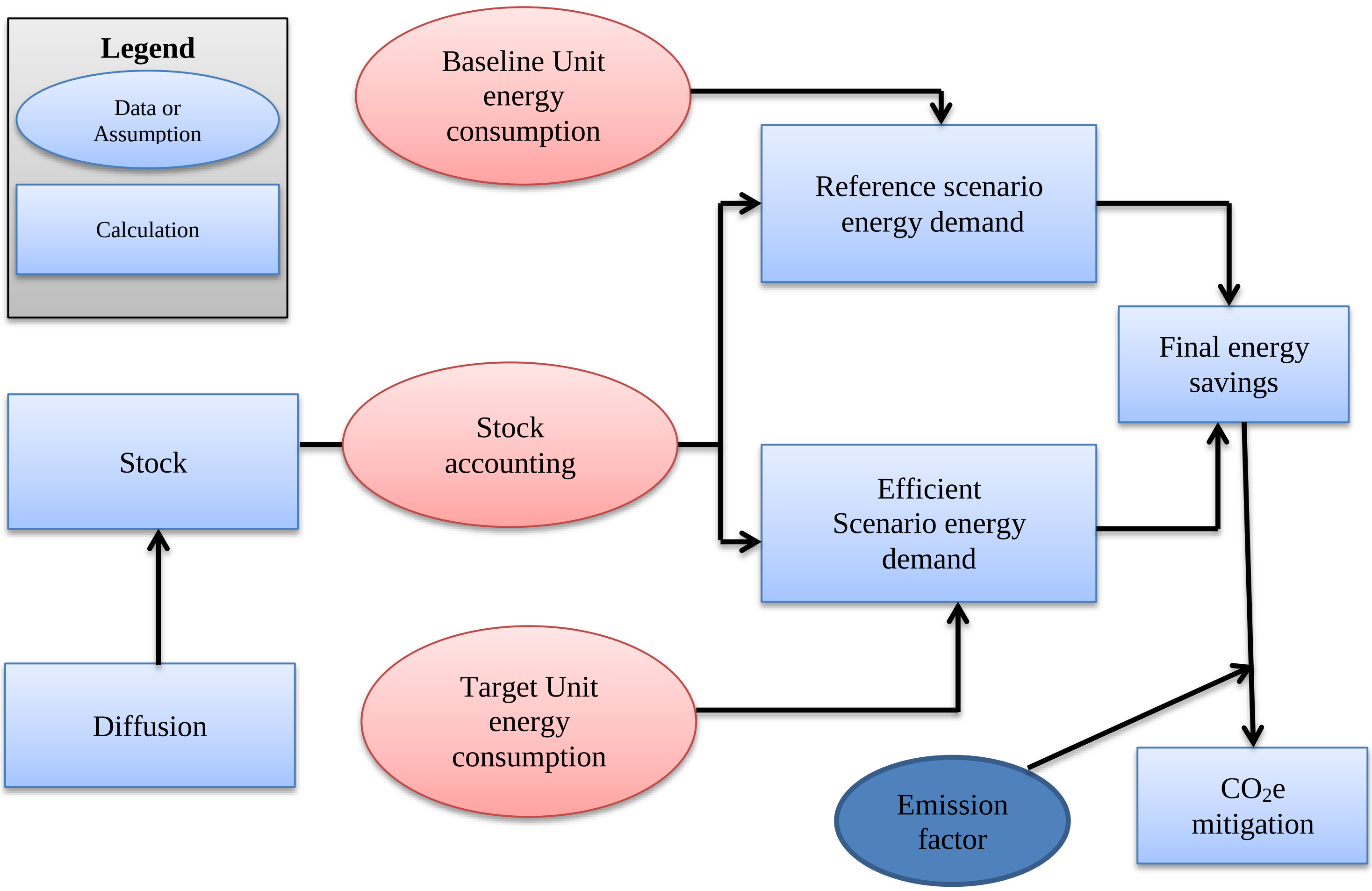

Figure 9: Flowchart of appliances energy savings and CO_2e mitigation calculation

4.2 LEAP data structure for the energy demand analysis

The first step for energy analysis in LEAP is designing a data structure. The data structure determines the kind of technologies and alternative scenarios that can be analyzed. Structure of the data is adapted based on the availability of data, the types of analyses, and unit preferences. Sector (slum household), end-uses (cooking, lighting and appliances) and devices (fuelwood stove, charcoal stove, kerosene stove, LPG stove, incandescent lamp, CFL, LED, fan, TV, refrigerator) are created in the demand tree structure. The LEAP data structure for the analysis is given below in the Figure 10. The same structure of effects was studied under each cooking technology as for fuelwood stove.

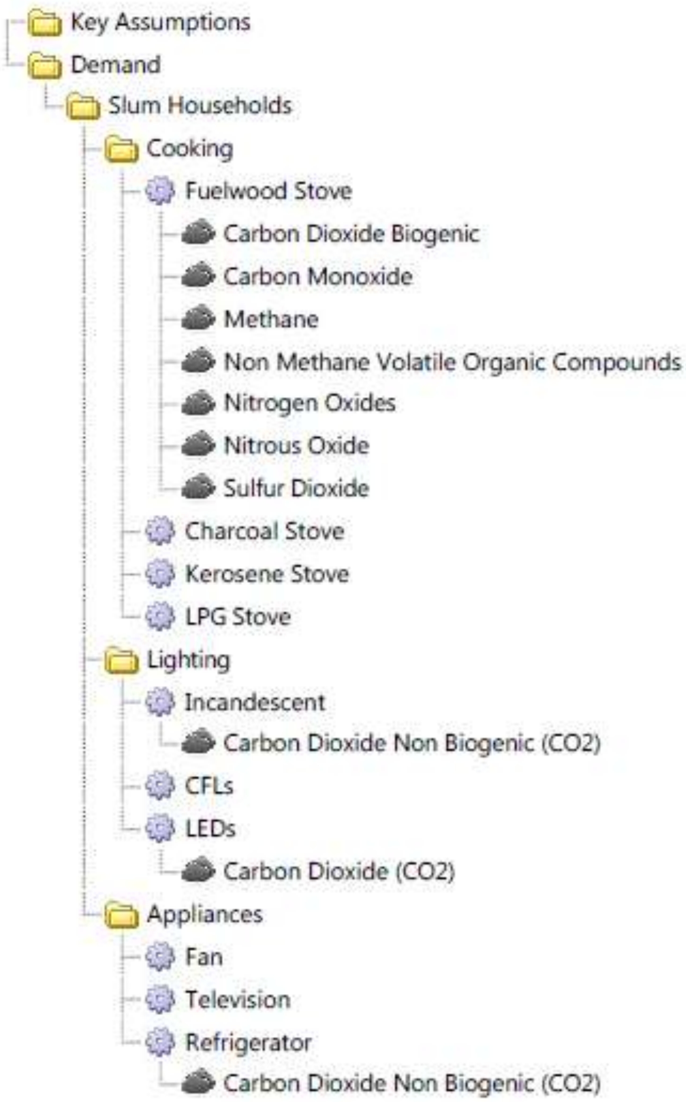

Figure 10: Flowchart of appliances energy savings and CO_2e mitigation calculation

4.3 Scenario description

Energy scenarios are envisioned for slums. Narratives of scenarios and quantification may provide useful insights in designing future slum development policies and programs to policymakers and organizations. Scenario development provides a good understanding of the future that might unfold and hence guidelines for policies and programs to take appropriate measures to create a desired future. UNEP (2002) defines scenarios as below:

"Scenarios are descriptions of journeys to possible futures. They reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play" (UNEP 2002).

Scenarios do not predict rather they provide a picture of different possible futures and discover different outcomes that might appear if basic assumptions are changed (UNEP 2002). Below is the description of the scenarios that might unfold due to changes in the driving forces involving slum dynamics that may have slums energy use consequences for the future in the long run. The time frame for the slums energy scenarios for the development of slums worldwide is medium to long range, 2014 (base year) to 2040. Two scenarios are envisioned based on the efforts (or lack of) put forth by organizations and governments' policies and programs in these two regions. The scenarios are: 1. Reference scenario, 2. Efficient scenario

4.3.1 Reference scenario

Slum households meet the basic level of energy services fully in 2040. However, the energy demands are met by inefficient appliances. This scenario is characterized by the current trend of slum dwellers moving out from slum conditions (with the help of economic growth) and joining normal urban residences with mostly unsustainable energy uses. The scenario represents current moderate efforts in supporting slums transition to normal urban residents sustainably, which is also fragmented and largely insufficient (Sietchiping, 2005). Normally governments in Sub-Saharan Africa and South Asia do not have policy formulated for the promotion of clean and sustainable energy especially for urban poor; however, they do have policies to increase energy access in general (GNESD, 2008).

With economic growth, several countries in Sub-Saharan Africa and South Asia are able to help increase their citizens' income and hence even pulling slum populations out of slums. Unfortunately, in absence of energy friendly and sustainable choices, these once slum population, now becoming the part of urban residents who are already locked-in fossil fuel based energy uses. The meager and fragmented current efforts are not able to tackle the enormity of the problem that comes with both in slum populations staying in slums and when they move to unsustainable residences and energy use with an increase in income. When slums are transitioning to unsustainable and inefficient energy uses i.e. buying an inefficient perhaps second-hand refrigerator, they are locked-in to unsustainable energy systems for years to come. This scenario highlights lost opportunity which if slum dwellers were provided with sustainable energy choices such as by slum upgrading practices, a considerable amount of energy savings could have been achieved.

At the same time, this scenario also characterizes slum populations which are represented by declining environmental conditions and services, and are in a process of inescapable decay. This means when they are unable to move out from slums from their efforts alone especially some parts in Sub-Saharan African (SSA). This situation takes place due to unwillingness, lack of capacity or sufficient resources or simply negligence from government and civil society's part. For instance, some countries in SSA do not have stable governance and political structure and hence although resource-rich they are the benefits do not transfer to the poor people who need it most. This scenario also shows that current piecemeal effort in solving the slum energy problems if further slipped out of hands, the slum situation might turn into despair as it is in some parts of Sub-Saharan Africa and South Asia where slum conditions are in declining stage. This highlights the real danger that lies in slums reaching towards declining stage mostly from tenets of human rights and sustainable development perspectives for a very long time.

In summary, the reference scenario attempts to define what might happen in a system if no external interventions were made and hinge on the assumptions about drivers (e.g. slum population growth, appliance diffusion, duration of appliance usage etc).

4.3.2 Efficient scenario

Basic needs of energy are fully met and sustainably in 2040, using efficient appliances. Efficient energy services are integrated into slum upgrading programs so that benefits of meeting energy needs outweigh the environmental penalties. This scenario demonstrates how far today's efficient energy technologies can take us in reducing slum dwellers energy use in the context of economic growth by fulfilling their increasing energy demands. The scenario employs efficient energy technologies for energy use in slum households through slum upgrading. Integrating sustainability concept in slum upgrading means use of improved cook stoves, modern cooking fuels, efficient appliances, improved lighting, and construction elements that reduce the environmental impact of construction, minimize the maintenance burden, and improve the quality of life. The prime criteria for ensuring sustainability could be affordability, technical feasibility, and low environmental impact. Moreover, this also improves the living conditions of slum dwellers in a holistic manner, a prime tenet of sustainable development.

Energy efficient technologies are selected based on their cost-effectiveness from slum households' context. Such efficient appliances and technologies may have the potential to be replicated for wider use based on economic feasibility among slum dwellers in Sub-Saharan Africa and South Asia. Energy demand from the efficient scenario is compared with the reference scenario energy demand for energy saving calculation.

From the literature review, it came out that so far none of the slum upgrading projects has focused on providing clean and sustainable energy for appliances, cooking, lighting, and cooling end use functions to the urban poor in both Sub-Saharan Africa and South Asia. However, there are projects which have only focused on one or two end-use functions. One such project is 'Kuyasa CDM project', which provided solar water heaters and efficient lightings to the urban poor in Kuyasa near Cape Town South Sub-Saharan Africa (Goldman, 2010). Apart from this, clean appliances and technologies are selected which may have the potential to be replicated for wider use based on economic feasibility among slum dwellers in Sub-Saharan Africa and South Asia.

4.4 Data sources and assumptions

In general, the data required to conduct the analysis are scarce for the study regions. The data are collected from a variety of sources to approximate objectivity and reduce uncertainty to the extent possible. Data used for the energy savings potential analysis are collected from various official sources and international organization publications. Data for slum population is taken from UN data (UN Data 2014). Historical slum population data from UN data is also used to calculate population growth rates for countries. Data for household size is collected from UN Habitat. Data for appliance diffusion and diffusion projection are collected from DHS STATcompiler from USAID, scientific report and papers, FAO, WHO, National Sample Survey Organization (NSSO) and World Bank reports. Similarly data for energy intensity and intensity projection are collected from various national and international organization publications such as International Energy Agency (IEA), World Bank, National Statistical Services, WHO, scientific report and papers, Lawrence Berkley National Laboratory (LBNL), The Energy and Resources Institute (TERI), Prayas Energy Group, etc. Most of these data are adapted from slum households' perspectives. Marker country data are used when a country has fluctuating or highly variable data that cannot be used to forecast. For example, the data for Ghana is used for West African region in the absence of country level data. Also, Regional estimates are used in absence of sufficient country level data.

The slum population data for Botswana is not available hence Zimbabwe's slum population growth rate is taken as they are adjacent countries and share socio-economic aspects. Most of the data for South Sudan are not yet available since the country was formed only in 2011. The data for Sudan before the division is taken instead. Similarly, most data (required for the analysis) for

Maldives, Swaziland, Réunion, Sao Tome and Principe, Seychelles, and Mauritius is also not available and hence they are not included in the analysis.

In general, data availability for the study regions (SSA and SA) are indeed challenging, however, this is not used to argue against modeling, instead of it is believed that the modeling process itself instigate the process of identifying and addressing data gaps (Tait et al. 2016). Modeling is a very data intensive process and the data limitations in the slums context in the low income and the developing countries are a real limitation. Therefore to address this problem, LEAP model that is easy to use with, flexible with data inputs, and can work with fewer data is used for the analysis.

The slum population percent growth which is an important input for the analysis is calculated by the below formula:

$$\text{Percent Growth (\%)} = \frac{\text{Pop}_{\text{BaseYear}} - \text{Pop}_{\text{Past}}}{\text{Pop}_{\text{Past}}} * 100$$

Where:

$\text{Pop}_{\text{BaseYear}}$ = Base year slum population

Pop_{Past} = Past slum population (most recent five years)

$$\text{Annual Growth Rate (\%)} = \frac{\text{Percent Growth}}{\text{Number of years}}$$

The annual growth rate (%) is the percent growth divided by the number of years.

Data for the last available five years (2009-2014) are taken to calculate slum population growth rates. It is because of the assumption that the last five years population is more relevant to calculate growth rates than the previous year's data. Although the general trend is increasing a number of households, there are few countries in both the regions where the number of slum households are decreasing in the periods between 2009 and 2014 such as India, Nepal, Malawi, Nigeria and Cameroon (UN Data 2014). On an average, slum population growth rate in the two regions is found to be 2.2% between 2009 and 2014.

4.5 End-use diffusion (activity level) methodology

Generally, appliance stock is not obtained as input data. However, in absence of appliances sales data as is the case with developing countries, appliance diffusion (ownership) rates can be used according to the following general relationship:

$$\text{Stock(y)} = \text{Diffusion(y)} \times \text{HH(y)}$$

Diffusion (y) = Number of units (owned) per household in year y

HH(y) = Number of households in year y.

Total stock is multiplied with unit energy consumption to obtain energy demand. End use energy consumption for a particular appliance depends on the efficiency as well as on the usage pattern. At the same time change in size and features of appliances play important role in determining the end-use energy consumption. Increasing wealth along with decreasing appliance prices drive the growth in appliances ownership, however, it slows down after reaching a saturation point. As slum dwellers become wealthier they choose appliances such as TV, refrigerator and washing machine. It can be assumed that with increasing wealth they will spend more time on entertainment, and will prefer less physical work and more comfort. Now, based on end-use efficiencies of appliances they can choose either efficient or inefficient one. Diffusion rates are a function of macroeconomic variables (income, electrification, and urbanization) as well as behavior, culture, safety, gender and climate (which determine the level of energy services). It is also important to make assumptions about the amount of time they use the appliances. It is assumed that inefficient appliances are used in reference scenario since their upfront cost is lower than efficient appliances. Inefficient appliances are linearly phased out and be replaced by efficient ones by 2040 in the efficient scenario.

Diffusion rates for slums locate between rural and non-slum urban households which can be verified by sources such as Statcompiler from DHS USAID (DHS 2014). Below I provide an example of TV and refrigerator diffusion from urban, rural, and Upper Accra sub-region (Table 5). Upper Accra sub-region is the urban center of the national capital Accra which has the highest percentage of slums. Interestingly the highest number of such appliances is owned by people in the Upper Accra sub-region. This shows that the wealthiest people live in the urban centers where slum households live as well for a better employment opportunity. However, it does not mean that slum households have a high penetration of such appliances. Still, when compared with the rural households', slum households own more appliances (Ibitoye, 2013). Hence it can be assumed that slum households own more of such appliances than rural but less than non-slum households of the urban region. A national average of end-use diffusion is used that represents a proxy for slum households end-use diffusion. In the below example, for Ghana, the diffusion percentage of slum households in the base year is 61.7% and 35.1% respectively for television and refrigerator.

Table 5: Diffusion data points (Ghana example)

Ghana	**Television (%) diffusion (2014)**	**Refrigerator (%) diffusion (2014)**
Urban	77.7	50.5
Rural	42.2	16.4
Greater Accra region (Sub-region with the the highest number of slum households)	83.9	59.6
National average	61.7	35.1

Source: DHS 2014

There is a historical account that development follows with urbanization in a given country. If a country has more rural population its national average for appliance ownership is lower than a country with higher urbanization rate. Therefore a national average of appliance ownership may reflect urban poor households' socio-economic condition and can be used as a proxy for their appliance ownership.

In the stock accounting, the stock of each end-use in each year is considered. It is assumed that energy efficient equipment is replaced gradually linearly and a complete transformation takes place until the modeling's end period, 2040. Since urban poor have extremely high internal discount rate and in most instances they purchase used equipment (Pachauri et al, 2012), there is a time lag of reaching efficient products to them compared to other urban households.

4.6 Energy intensity calculation

The next research step is to collect estimates of the average baseline unit energy consumption (UEC). UEC is dependent on the typical products used such as the size of a refrigerator, the average efficiency of the product currently available on the market, and use patterns. Use patterns are driven by several factors, one of them for example is climate which is the main determinant of space cooling end use. Further, stock accounting tracks the total number of energy products available for use in a particular year. The difference between energy use in the stock in the reference scenario and efficient scenario provides energy savings.

Estimates of the average unit energy consumption (UEC) for reference and efficient scenarios are determined. Estimates of the average baseline unit energy consumption are gathered for reference scenario. This is dependent on the typical products used (such as the size of a refrigerator, for example), the average efficiency of products on the market, and use patterns.

Design options for end uses are analyzed based on efficiency improvements which determine UEC for the efficient scenario. The efficiency target levels represent technologies/design options that are available and cost-effective now. Efficiency target levels also aim to include a more realistic maximum cost-effective efficiency level, which means technologies that are already available and cost effective or would be cost effective very soon. Technical potential is not analyzed since the study deals with a poor population in the developing countries. Due to the complexity of the number of countries and end-uses considered, simplified assumptions on aggregate efficiency levels on the regional level are made.

The baselines and targets are assumed to be constant during the forecast period. Frozen efficiency is assumed in the reference as well as in the efficient scenario which means the market-driven efficiency that may happen in the reference scenario may also happen in the efficient scenario hence energy savings will be constant.

4.6.1 Cooking energy use

Cooking is the most basic end use, therefore, it is assumed that every household has a cooking device. Cooking is the dominant energy end use function in developing countries. Cooking fuels can be divided into solid fuels, and liquid & gaseous fuels based on the cleanliness and efficiency of combustion of the fuel. Solid fuels refer various biomass and coal while liquid and gaseous fuels refer to biogas, coal gas, liquid petroleum gas (LPG), natural gas and electricity which are termed as modern fuels (Mainali et al., 2012). Cooking devices that are included in the study are fuelwood stoves, charcoal stoves, kerosene stoves and LPG stoves which are the dominant cooking devices in the two regions. Energy intensity is multiplied by the number of households in order to obtain the cooking energy demand.

4.6.2 Lighting services

Once electricity is introduced in slum households, lighting is generally the first end-use. Lighting energy use is primarily determined by the number of fixtures installed in the households, the type of lamp, and use of hours (McNeil et al. 2008). Slum households use little electricity for lighting since just one or two lighting fixtures may be sufficient as they live in small spaces. At the same time, they might also bear a high cost for electricity and use other fuels for lighting purpose such as kerosene (ibid). Three lighting technologies- Incandescent lamps, CFLs, and LEDs and a share of them are analyzed in UEC calculation. Fluorescent tubes are used in developing countries but not so much in slum households. Lighting consumption is determined by assuming certain wattage per lamp.

The share of each type of lighting lamps among slum households having access to electricity need to be estimated. Incandescent, CFLs, and LEDs. LEDs and CFL lamps use very less energy compared to incandescent bulbs. In order to calculate lighting consumption, assumptions are made for wattage per lamp/bulb. McNeil et al. (2008) found that commonly applied wattage is 60W for an incandescent bulb, and 15W for CFLs. Commonly applied wattage for LEDs is 7W (Design Recycle Inc. 2015). Annual light consumption is calculated by the following equation:

$$UEC(kWh) = No.of\ pointsXHrsX365X(\%ILX60 + \%CFLsX15 + \%LEDsX7)/1000$$

Incandescent bulbs are still common in the residential sector of developing countries and in urban poor households. Although CFLs penetration differs between countries, a significant energy savings can be achieved by switching to CFLs. LEDs are still not adopted by slum households but given this is an upcoming technology and as their prices go down these would soon become popular among low-income urban households including slum households. It is assumed that in the reference scenario, slum dwellers use standard form of light such as incandescent light bulb and some CFLs, and only a low share of households fully use efficient lights such as CFLs/LEDs. In the efficient scenario the share of efficient forms of light- CFLs and LEDs increases and reaches saturation by 2040.

Compact fluorescents lamps (CFLs) appeared as the first competitor and gained a traction against incandescent. They are much more energy efficient however, still has some drawbacks. CFLs contain mercury, a toxic metal that is bad for the people and the environment which also means that a propped, careful recycle or disposal is important. Next, a lot of CFLs do not dim that makes them unsuitable with dimmable fixtures. Lastly, CFLs come in spiral shape, prompting people to choose a traditional bulb-shaped lamp for maintaining certain aesthetics (Anderson 2016). Due to these drawback of CFLs despite being more efficient compared to incandescent lamps make them less preferable than LEDs.

4.6.3 Appliances energy use

The energy demand of urban poor households highly depends on income levels. The poorest household with electricity access will use lighting services only. Households purchase energy appliances in an order that can be understood with the help of an appliance 'ladder'. Urban poor households with increasing income levels buy fans as the first appliance, second a television and then a refrigerator (McNeil et al., 2008). In order to calculate appliances energy use, the appliance stock first need to be modeled by forecasting diffusion. The stock is further combined with unit energy consumption of devices to obtain total appliance energy use.

Fan: After lighting energy use, fans are the first electric appliance which slum dwellers buy corresponding to increasing level of income. Fans energy use depends on the length of the season and usage hours per day. Cooling degree days determine the length of the season in which fans are used. Data for baseline unit energy consumption are collected and used in the reference scenario. Available efficient technology is studied which gradually becomes the norm in the efficient scenario.

Television: Television is a fast-evolving product. However, as TV is mainly manufactured by large multinational companies for global markets it is quite uniform across countries. Standard size, image technology and viewing time is used for UEC calculation for television which is commonly used among urban poor households. Currently, most of the urban poor use CRT TVs (color) but image technology is currently shifting swiftly towards LCD. Market share projections of the two technologies are combined with the technical improvements to build reference and efficient scenarios. Mainly size and image technology affect the energy use of a TV. A mix of CRT and LCD technologies are covered in the analysis. The assumption is that CRTs decrease at a current rate and their lost market share will be filled by LCD TVs.

Refrigerator: International efficiency and UECs for refrigerator are widely available as they are regulated products. Refrigerators occupy a high share of electricity consumption and also one of the most desirable products. Although refrigerators are variable products between countries, dominant product types can be identified due to increasing trends towards internationalization of major white goods. It is known that slum dwellers use pretty inefficient products as they buy second-hand products in most cases which mean there is a gap in reaching efficient products to them. Target efficiency level for slum households is assumed for both the regions. Identification of baseline products from both regions and related electricity consumption (kWh/year) are the steps in UEC calculation.

4.7 Final energy demand analysis

Total final energy use (TFEU) for cooking, lighting, and appliances are calculated by summarizing final energy use for all end-use types for each year and for the modeling period:

$$TFEU_t = \sum FinalEnergyUse_{it} ,$$

Where, i – end-use type, and t – a certain year

Final energy savings is calculated by comparing efficient scenario energy demand and Reference scenario energy demand.

$$\Delta E(y) = E_{\mathrm{Re}\,f}(y) - E_{Eff}(y)$$

Δ E (y) = Energy saving in year y

E_{Ref} = Energy use in Reference scenario

E_{Eff} = Energy use in Efficient scenario

First, current energy demand is created by specifying data for the base year which provides the foundation for the reference and efficient scenarios. Further reference scenario is developed assuming a continuation of current trends. Now, interventions are evaluated by using alternative scenario i.e. efficient scenario. The modeling follows an end use, demand driven approach which means analysis starts from the end use of energy. Under this approach, the demand program divides the society in a hierarchical tree structure of three levels: sectors, end-uses, and devices. An example of one branch of such structure could be: Slum households (sector), lighting (end use) and incandescent bulb (device). For each device, a fuel type (electricity in this example) and the average consumption are specified. Energy use is then analyzed by breaking down total demand into the overall sector (slum households), end use (as lighting) and devices (as fan).

Final energy demand calculation is a disaggregated, end-use based method for modeling the requirements for final energy consumption in slums energy system. Economic, demographic and energy-use information are applied to construct reference and efficient scenarios which examine the changes in total and disaggregated consumption of final fuels with time. Activity levels (such as (end use diffusion, number of households etc.) is used in demand analysis as a measure of the social/economic activity for which energy is used. Hierarchy of branches is created for demand analysis structure in LEAP. Activity levels are described in absolute terms such as number and growth rate of slum households at one level of the hierarchy and in proportional terms such as percentage saturation or share of end-uses in the other level of the hierarchy. The product of these terms provides the overall activity level for a given device. Efficiency is termed as percentage annual average thermal efficiency of a device. Energy intensity is the energy consumption per unit of activity level. Final energy intensity is generally given at the last level of technology branches. Energy usage is calculated by multiplying the total activity level for the device with its energy intensity or unit energy consumption.

Energy demand is calculated for the base year and for the subsequent future years for each scenario. It is noteworthy that all scenarios develop from the base year data. Each technology branch in LEAP is exclusively associated with a certain fuel hence the total final energy demand for each fuel is also calculated. Energy demand data structure is disaggregated into different levels representing sectors and/or subsectors, end-uses and devices in LEAP to perform a final energy demand analysis. A below example showing the activity level table (figure 11) from LEAP illustrates this approach:

Activity Level | Final Energy Intensity | Demand Cost | All Variables

Activity Level: A measure of the social or economic activity for which energy is consumed. [Default="0"]

Branch	Expression	Scale	Units	Per
Slum Households	23.42	Million	Household	
Appliances	100	Percent	Saturation	of Households
Fan	70	Percent	Saturation	of Households
Television	47	Percent	Saturation	of Households
Refrigerator	16	Percent	Saturation	of Households

Figure 11: An example of LEAP activity level table

Activity levels for the top level is usually described in absolute terms as revealed above - the number of households is 23.42 million in the base year, while other levels are labeled in proportionate terms. In the example shown above, 16% of slum households own some type of refrigerator, and all refrigerators are existing or less efficient models. More efficient models have not been owned by slum households in the base year. Although the data in the above table is shown for the base year only, values are changed accordingly in the reference and efficient scenarios to reflect the combined effects of changes at several levels, for example, the ownership and share of end uses, the growth rates of slum households etc.

4.8 GHG emissions reduction potential

Once the final energy demands from the reference and the efficient scenarios and the energy savings are estimated, the GHG emissions and emissions reduction potential can be calculated in the LEAP. The calculation method of GHG emissions in the reference and efficient scenarios uses LEAP's carbon emission factors for countries. Comparing the GHG emissions from the reference and the efficient scenarios provide the magnitude of the GHG reduction potential as a contribution to climate change problem from slum households' transition towards more energy efficient energy use. The calculation method of the GHG emissions from final energy savings and emissions reduction potential is given in the chapter 6.

Chapter 5. Energy savings potential

This chapter is in line with fulfilling the research gap in knowledge by providing evidence based energy efficient pathways in urban poor context. The chapter starts off with estimating the level of current end-use demand, and to forecast growth in slums energy demand until 2040 by end use in the reference scenario. Next, efficient scenario is created by introducing efficient appliances and forecasting the energy demand until 2040. By comparing the two scenarios, magnitude of the energy savings from slums transition to efficient energy system is obtained. Overall final energy demand and savings are calculated using the same approach as shown by India example. Research results are described in terms of the energy savings of the slum households in Sub-Saharan Africa and South Asia from application of efficient technologies in efficient scenario (desirable) against the reference scenario until 2040. To check the validity of the results, calibration in the base year is carried out.

The objective in the research is to give not so much precise estimates of potential savings but as a general idea of their magnitude. The energy consumption from each appliance depends on its size, type, and use. A single representative size and a single representative type (the most common type and size for each appliance) are identified for each appliance based on their popularity in the market. I do not expect that this simplification in the analysis will seriously bias the results of the analysis in either direction, because the impact will be off-setting to some extent. For example, larger savings from bigger appliances will be off-set by smaller savings from smaller appliances. I also exclude technological change that is likely to lower, to some extent, the consumption of the most common as well as efficient (& cost effective) appliance hence the total energy savings will approximately remain the same.

Long range Energy Alternatives Planning System (LEAP) is used to forecast activity level, final demand, energy savings, and emissions associated with the realization of efficient scenario. One of the main reasons to use LEAP is that it represents developing countries characteristics and economies very well (Bhattacharya and Timilsina 2009; Urban et al 2007, p. 3478). The following analysis is done for the base year, reference, and efficient scenario for India. I have also calibrated the results with the existing studies.

Below I provide a detailed energy saving potential analysis for India as an example of energy demand analysis undertaken in LEAP. All countries in the two regions are analyzed in the same way using the relevant data. Overall final energy demand and energy saving results are given towards the end.

5.1 Base year activity level, energy intensity and demand

About 90% of the slum households are electrified (Census of India 2011) and use electricity for lighting and other devices such as fan, TV and refrigerator if available. The total slum population is 99 million (UN Data 2014). Given the current household size of 4.47 (census of India 2011), the total number of households comes out as 22.02 million.

5.1.1 Lighting

Currently majority of households about 90% use incandescent lamps and only 10% use CFLs for lighting (Singh 2014). Currently LEDs penetration in the slum households is none. Lights are used for 4 hours per day. Average wattage for incandescent lamp is 55 W for the base year (TERI 2006, Prayas 2009, McNeil et al. 2008). There are two lighting points per households

(Fulkerson et al. 2005). The electricity consumption for lighting (annual energy intensity) for incandescent lamp is calculated as 160, for CFL is 43.80, and for LEDs is 20.44 kWh/yr/household. Energy consumption from incandescent lamps (3100 million kWh) is about 31 times more than the CFLs (100 million kWh) whereas no consumption comes from LEDs as they do not exist in the base year (Figure 11). The data and assumptions to reach these numbers are given in the table 6.

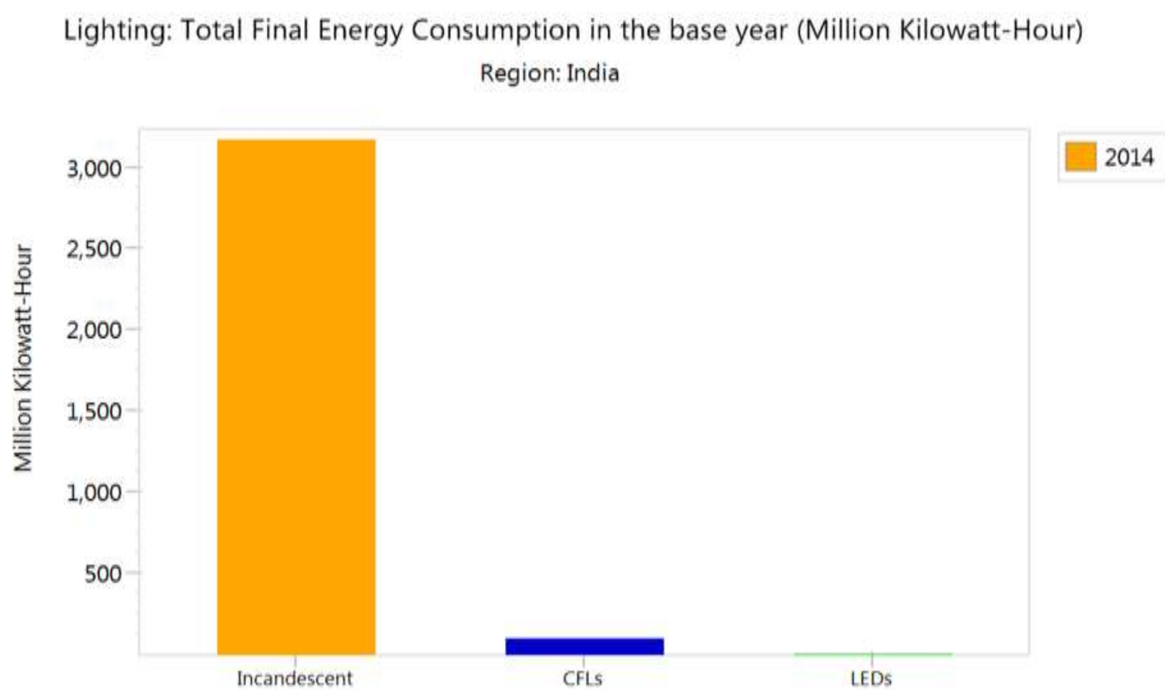

Figure 12: Lighting energy demand in the base year

5.1.2 Fan

70% slum households have fan (NSSO 2010). Fans are needed for about 200 days in a year in India and in South Asian sub-continent. The average wattage for fan is 70 W and the most common technology is 1200 mm sweep for blades (TERI 2006, Business Standard 2008). The electricity consumption from fan use is 84 kWh per year (annual energy intensity) on average per household in the base year (Table 6). Energy consumption from the fan is the highest (1300 million kWh) among appliances (Figure 13) whereas consumption from refrigerator and TV comes out as about the same in the base year for all slum households.

5.1.3 Television (TV)

TV diffusion is 44% (NSSO 2010). TV is turned on for four hours per day. The most common technology used in the base year is CRT, however LCD penetration is not known. Average wattage used in studies is 80 W (DERC 2006, TERI 2006). The annual electricity consumption or energy intensity for TV is calculated as 116 kWh/household (Table 6). Total energy consumption from TV in the base year is 1130 million kWh (Figure 13).

5.1.4 Refrigerator

Refrigerator diffusion is 15% (NSSO 2010). The most common technology used by households is direct cool (180 ltr) and frost free (180 ltr). Studies cite refrigerators annual energy intensity as 350 kWh per household for these two technology mixes (Boegle et al. 2009, LBNL 2007, TERI, 2006). Total energy consumption from refrigerator in the base year is 1180 million kWh

(Figure 13). A summary of assumptions, base year technology, base year UEC and sources for appliances are given in the table 6.

Refrigerators in Sub-Saharan Africa however consume a lot more energy compared to refrigerators in other regions in developed countries (Van Buskirk et al., 2007). It is because of many factors such as use of second-hand appliances, ambient temperature, erratic electricity supply, humidity etc. A sizeable fraction of second hand refrigerators in the market usually come from Europe. As a result, their efficiency is way less than the new appliances (Van Buskirk et al., 2007). Several countries in Sub-Saharan Africa is banning and has already successfully banned the importation of second-hand refrigerators therefore energy consumption and efficiency should improve incrementally even in the reference scenario (Halff, Sovacool, and Rozhon 2014). For Sub-Saharan Africa, energy consumption from 1 door, inefficient, probably second-hand refrigerator (1140kWh/year) is used in the base year. Energy consumption from 1 door EU B level refrigerator (317 kWh/year) is used in the efficient scenario that is achieved in the end year (Unlimited Energy Resources (pty) ltd, 2012).

Table 6: Unit level assumptions and data sources for appliances in the base year

Appliances	**Technology /efficiency**	**Diffusion in the base year (%)**	**UEC (kWh/yr)**	**Sources**
Incandescent lamps (4 hrs/day, 365 days/yr, two lamps/households)	55 W	90% share	160	TERI 2006, Boegle et al. 2009, UNEP 2012
CFLs (4 hrs/day, 365 days/yr, two lamps/households)	15 W	10% share	43.80	TERI 2006, Boegle et al. 2009, UNEP 2012
LED (4 hrs/day, 365 days/yr, two lamps/households)	7 W	0% share in 2014; 5% share in 2020	20.44	Design Recycle Inc. 2015
Fans (6 hrs/day, 200 days/yr)	70 W (size of 1200 mm sweep)	70	84	TERI 2006, Business Standard 2008, Rathi, Chunekar and Kadav 2012
TV (4 hrs/day, 365 days/yr)	Mix of technologies (CRTs, LCD), 80 W	44.2	116	DERC 2006, TERI 2006, NSSO 2010, Park et al. 2014, Rathi, Chunekar and Kadav 2012
Refrigerators	Direct cool (180-200 ltr) and Frost free (180-200 ltr)	16	350	LBNL 2007, TERI 2006, NSSO 2010, Boegle et al. 2009

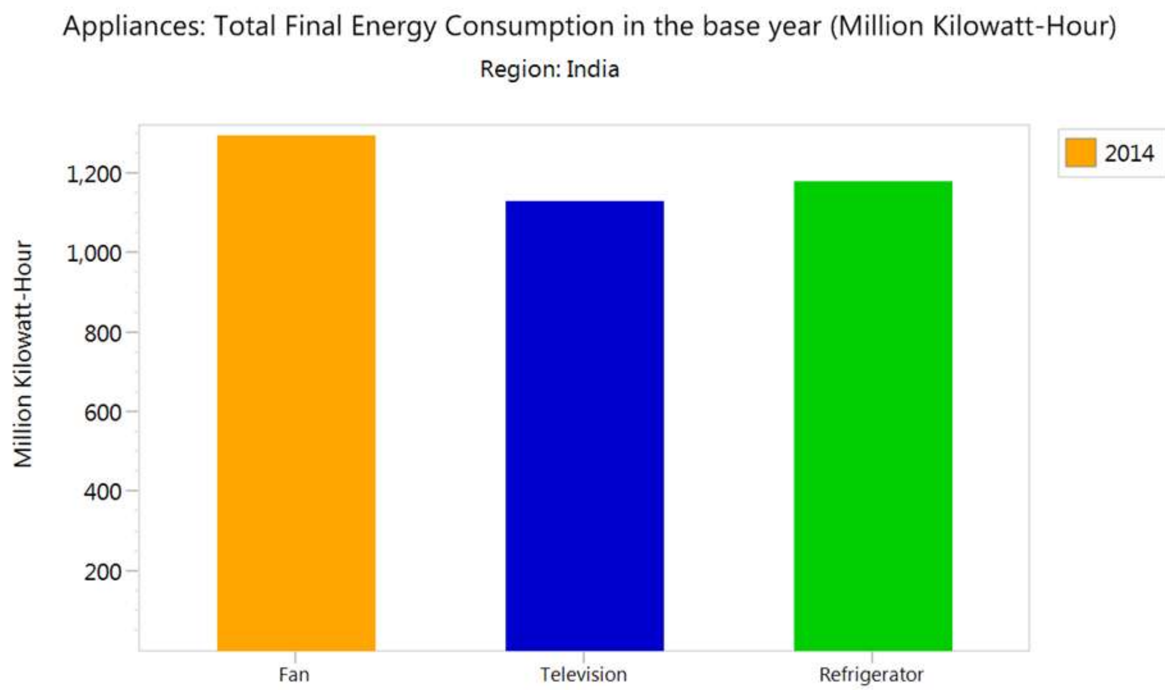

Figure 13: Appliances energy demand in the base year

5.1.5 Cooking

In India, 850 million people, majority of rural population (about 88%), currently cook with solid biomass fuel in open fires or rudimentary mud stoves (GACC 2013). This means 12% urban population, apparently urban poor, cook with solid biomass fuel which turns out to be 102 million (850*12%). According to UN data, slum population in India in 2014 was 99 million (UN 2014). UN data is used for slum population in the analysis.

All households have at least one type of cooking device. As presented in the below table (Table 7), most of the electrified slum households in India use kerosene (54%) and LPG (30%) stoves along with biomass (fuelwood, dung, and crop residue, 47%) and charcoal (6.6%). 31 Liters of kerosene, 64 kilograms of LPG, 700 kilograms of biomass and 52 kilograms of charcoal are consumed annually per household (Khandker, Barnes, and Samad, 2010). Energy consumption from fuelwood stands out as the highest with about 110 million gigajoule in the base year followed by LPG (20 million gigajoule) and kerosene (13 million gigajoule) (Figure 14). Although kerosene and fuelwood are used by roughly half of the slum households, energy consumption is more than eight times with the fuelwood as it being the most inefficient source of cooking energy.

Table 7: Unit level assumptions and data sources for cooking in the base year

	Diffusion (%) in the base year	**Annual energy intensity/household (kg)**	**Source**
Kerosene Stove	54	31.2 liter	Khandker, Barnes, and Samad, 2010
LPG Stove	30	64.2 kg	Khandker, Barnes, and Samad, 2010
Fuelwood Stove	47	700 kg	Census of India 2011; Khandker, Barnes, and Samad, 2010, IEA 2006
Coal/Charcoal Stove	6.6	51.6 kg	Khandker, Barnes, and Samad, 2010

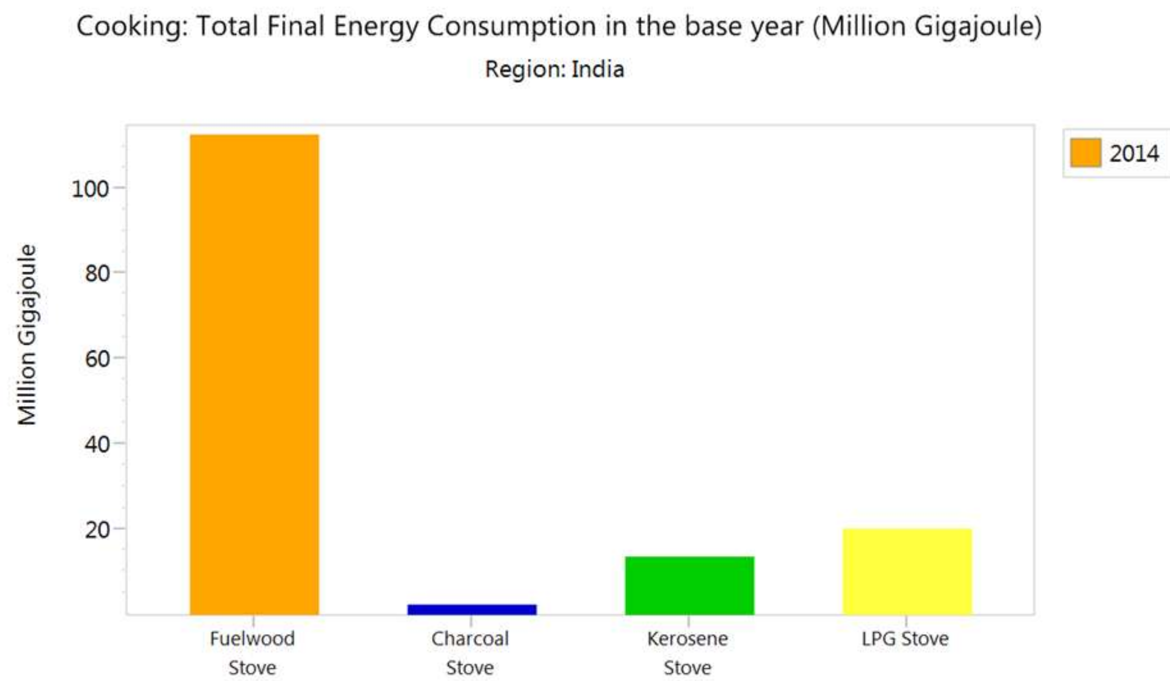

Figure 14: Cooking energy demand in the base year

5.2 Calibration in the base year (India)

Table 8: Electricity consumption, India (Billion Kilowatt-Hour)

Fan	Television	Refrigerator	Incandescent	CFLs	Total	Number of Households (million)	Electricity demand per household (kWh)
1294	1129	1180	3170	96	6869	22.02	**312**

Electricity demand per household for India in the base year comes as 312 kWh. World Energy Outlook (WEO) assumes an initial threshold level of electricity consumption for urban household to be 500 kWh per year (IEA 2012). Given that WEO threshold is for average urban household in the developing world and does not reflect low income urban population, 312 kWh seems a reasonable figure to represent slum household's electricity consumption in India. This way monthly electricity consumption is 26 kWh per household. The average household size in Indian slums is 4.47 and therefore annual electricity demand per capita comes out as 70 kWh. WEO (2012) has set minimum urban electricity consumption as 100 kWh per person per year.

Table 9: Cooking energy consumption in the base year, India (million Gigajoule)

Fuelwood Stove	Charcoal Stove	Kerosene Stove	LPG Stove	Total	Number of Households (million)	Cooking energy demand per household (Giga joule)
112	2.2	13.4	20	147.6	22.02	**6.70**

Cooking energy demand for India comes out as 6.70 GJ per household. According to Khandker, Barnes, and Samad, 2010 the urban energy poverty line in India is 2.4 kgOE per person per month which translates into 5.4 GJ per household per year (cooking, lighting and appliances). Also other authors report (Sanga and Januzzi, 2005; Demierre et al., 2014; Couture, and Jacobs, 2016) that energy needed for cooking per person is 1GJ per year which will be 5-6 GJ per year per household (given on average 5-6 persons per household). Most of the slum households are near urban energy poverty line therefore a number close to 5.4 GJ may provide a basis for this analysis in the base year. After converting annual electricity demand per household (312 kWh) into GJ and adding with annual cooking energy demand per household (6.70 GJ) gives 7.8 GJ.

Annual electricity demand per household – 312 kWh = 1.1 GJ

Annual cooking energy demand per household = 6.70 GJ

Total energy demand per household = 7.8 GJ

Total energy demand, 7.8 GJ is close enough with the urban energy poverty line 5.4 GJ analyzed by Khandker, Barnes, and Samad, 2010. This may provide a basis that energy demand obtained in this analysis is comparable with the existing research.

5.3 Reference scenario activity level, energy intensity and final demand

India is experiencing a decreasing slum population in the last five years. The number of households is expected to decrease from 22 million in the base year at the rate of 1.3% per year (UN Data 2014).

5.3.1 Lighting

It is expected that despite widespread campaigns in India such as Bachat Lamp Yojna[2] and Unnat Jyoti by Affordable LEDs for All (UJALA)[3] to replace incandescent lamps with CFLs, and LEDs, 20% households will still be using incandescent lamps in 2040 in the reference scenario. For example initiatives such as Bachat Lamp Yojna program sought to replace 400 million incandescent lamps with CFLs at a same price in which households buy cheap and inefficient incandescent lamp. Bachat Lamp Yojna is currently being replaced with UJALA scheme that aims to replace incandescent and CFLs with LEDs.

[2] https://www.bijlibachao.com/government-programs/bachat-lamp-yojna-bly-a-scheme-by-bee-to-promote-energy-efficient-lighting.html

[3] http://economictimes.indiatimes.com/news/economy/policy/ujala-will-be-implemented-across-country-by-2019-piyush-goyal/articleshow/52053959.cms

However annual lighting intensity for incandescent lamp, CFLs, and LEDs increases to 642, 175, and 81.76 kWh per households respectively with increase in hours of use and number of lamps in 2040 (8 hrs/day, 365 days/yr, four lamps/households). The final energy consumption reaches to 2000, 1645, and 256 million kWh respectively for incandescent, CFLs, and LEDs in 2040. It is noteworthy that although only 20% households use incandescent lamps in 2040, energy consumption is still the highest.

5.3.2 Fan

The fan diffusion in 2040 reaches to current US or China fan diffusion level i.e. 153% (McNeil 2008). The annual intensity increases to 168 kWh per household in 2040. The final energy consumption reaches to about 4000 million kWh in 2040.

5.3.3 Television

By 2040 television diffusion will reach the current level of China, i.e. 114% (McNeil 2008) with a growth rate of 2.75% (ITU 2013). The annual intensity increases to 175 kWh per household by 2040. The final energy consumption reaches to about 3100 million kWh in 2040.

5.3.4 Refrigerator

With increase in income, households purchase larger appliances therefore annual refrigeration intensity rises to 588 kWh per household by 2040. The final energy consumption reaches to about 9200 million kWh in 2040.

Altogether energy consumption for appliances (fan, TV, and refrigerator) increases very rapidly by 7.4 times in the 2040 compared to 2014 in the reference scenario in India.

A summary assumptions, reference technology and reference UEC are given for appliances in the below table.

Table 10: Assumptions, reference technology and reference UEC for appliances

Appliances	**Technology /efficiency**	**Diffusion in 2040 (%)**	**UEC (kWh/yr)**
Incandescent lamps (8 hrs/day, 365 days/yr, four lamps/households)	55 W	20% share	642
CFLs (8 hrs/day, 365 days/yr, four lamps/households)	15 W	60% share	175
LED (8 hrs/day, 365 days/yr, four lamps/households)	7 W	20% share	81.76
Fans (12 hrs/day, 200 days/yr)	70 W (size of 1200 mm sweep)	153	168
TV (6 hrs/day, 365 days/yr)	Mix of technologies (CRTs, LCD, LED), 80 W	114	175
Refrigerators	Direct cool and Frost free	100	588

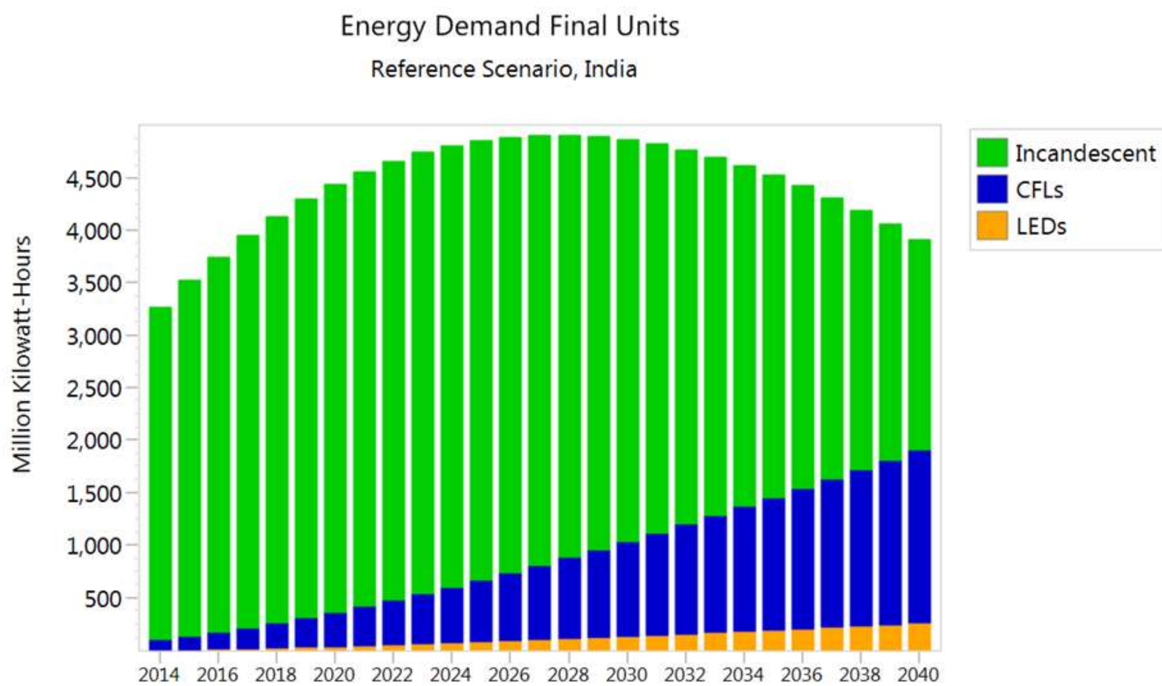

Figure 15: Lighting energy demand in the reference scenario by 2040

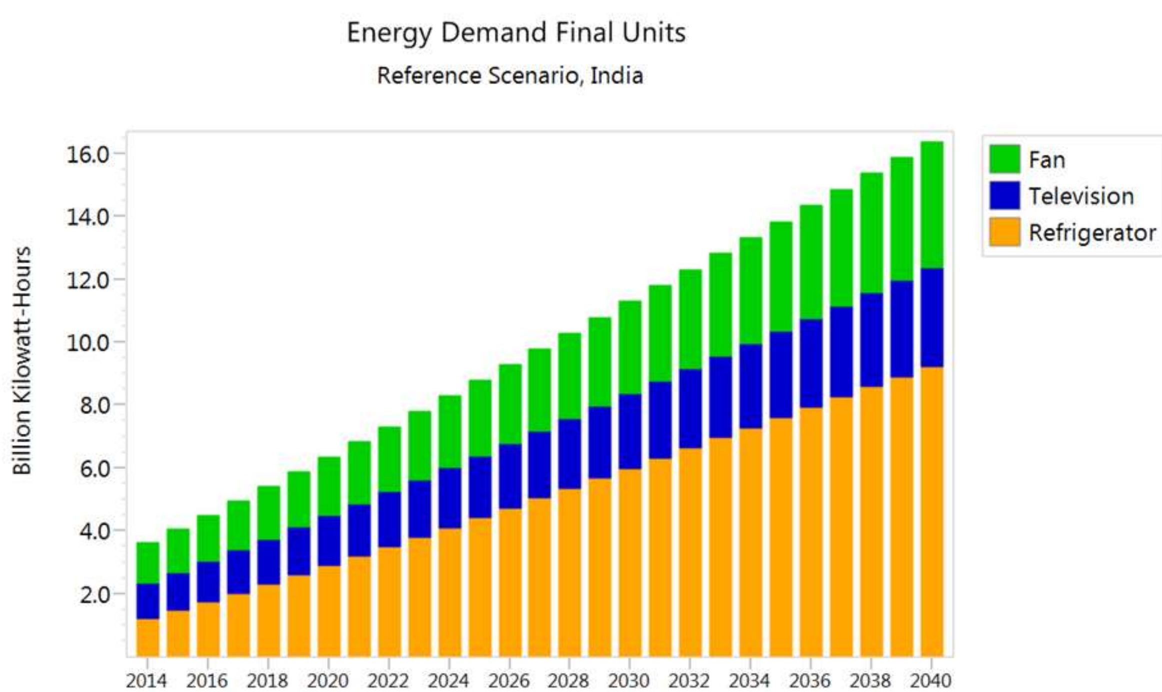

Figure 16: Appliances energy demand in the reference scenario by 2040

5.3.5 Cooking

Because of a slow decline in the fraction of households using biomass – about 0.26% per year between 2001-2011 (GOI 2011) and coupled with the rate of population decrease (about 1.3% per year), the absolute number of biomass users in 2040 are set to decrease by approximately half compared to the base year fuelwood energy consumption. Also the fuelwood annual intensity decreases to 480 kg per household due to more dependence on LPG. Use of coal/charcoal is already not significant and is further set to decrease to 36 kg by 2040. If the current subsidy on kerosene continues, the number of households that use kerosene for cooking will remain almost same in 2040. Annual energy intensity for kerosene decreases to 24 liters per household (Rao 2012).

About 80% households use LPG as the main cooking fuel by 2040. However not all households are able to use it due to high upfront cost, lack of infrastructure and governmental support. The annual energy intensity among slum households in 2040 reaches 84 kg per household per month which is less than the current urban intensity of LPG use (Khandker, Barnes, and Samad, 2010, pp. 32). Recently government has reduced the number of subsidized LPG cylinder per households and increased the price of LPG in an effort to reduce its rising fuel subsidy budget (GSI 2012). Since government exports most of the LPG from outside of its borders, continuous future use of LPG raises questions regarding price volatility and affordability by poor households.

The final energy consumption for fuelwood, charcoal, kerosene, and LPG reaches to about 51, 0.7, 4.1, and 50 million gigajoules in the reference scenario in 2040 (Figure 17).

Table 11: Assumptions, reference technology and reference UEC for cooking

	Diffusion in 2040 (%)	**Annual energy intensity/household**
Kerosene Stove	30	24 liter
LPG Stove	80	84 kg
Fuelwood Stove	Growth rate (-0.26%)	480 kg
Coal/Charcoal Stove	4	36 kg

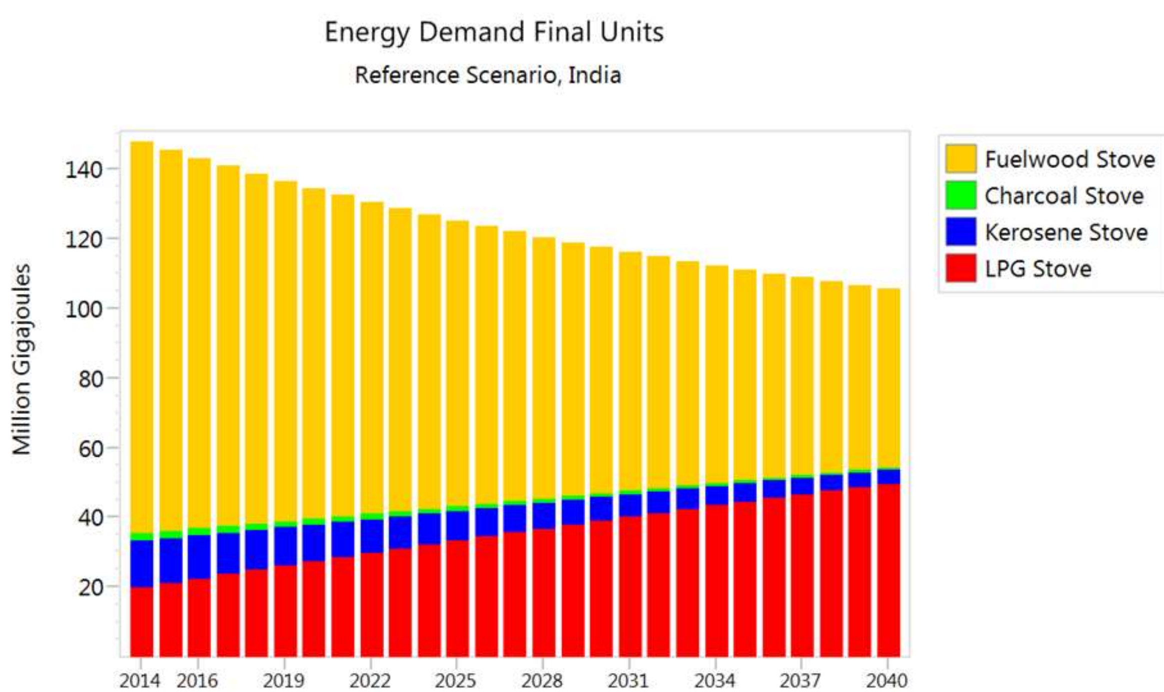

Figure 17: Cooking energy demand in the reference scenario by 2040

Figure 18 shows that in 2014, overall final energy consumption from India was 48 billion kWh. Final energy consumption will increase only a little over the modelling period because of fuel switching that take place in cooking and lighting end uses and will reach to 50 billion kWh in 2040.

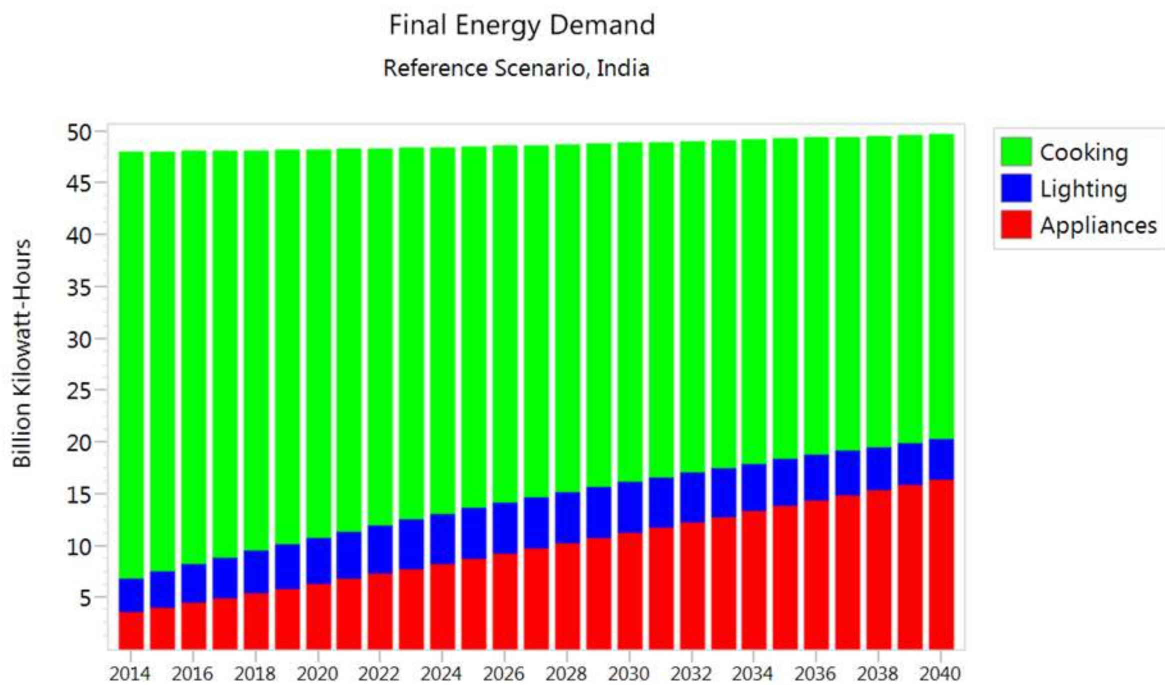

Figure 18: Final energy demand from all end uses in the reference scenario by 2040

Given the level of assumptions and approximation in order to estimate the energy demand and GHG emissions, it would be useful to have a simple uncertainty assessment for the key results. Since slum growth rates represent key uncertainty for the estimation of final energy demand and GHG emissions, I have analyzed the impact of varying slum household growth rates in the case of India, the country with the highest number of slum households in the base year (22 million). The current projection for slum growth rate which is used in the analysis is -1.3%. I have assessed the impact of +/-100% to this slum household growth rate on the energy demand and GHG emissions in the reference scenario. This range (-2.6% to 0% growth rate) is an arbitrary one and rely on the way slum development policies and strategies are adopted and implemented in the next two to three decades.

When the growth rate is decreased from -1.3% to -2.6% in the reference scenario, the final energy demand is reduced from 50 billion kWh to 36 billion kWh whereas when growth rate is increased to 0%, the energy demand increases to 70 billion kWh in 2040. However, when the growth rate is decreased from -1.3% to -2.6% in the reference scenario, the GHG emissions is further reduced from 25 million tonnes CO_2 Eq. to 18 million tonnes CO_2 Eq. whereas when growth rate is increased to 0%, the GHG emissions increases to 35 million tonnes CO_2 Eq in 2040. Therefore the approximate range for energy demand and GHG emissions for India in the reference scenario is respectively 36-70 billion kWh and 18-35 million tonnes CO_2 Eq in 2040. This large range of the results reflects the high uncertainty of the overall impact of the slum growth rate on the energy demand and GHG emissions of slum households. The same situation is likely to hold true for the rest of the countries which may affect the total energy savings and emissions reduction potential. This uncertainty assessment explains the importance of the quality of the slum households socio-economic development that may take place in the future. The quality of slum households development will determine their energy and emissions dimensions which closely hinges to the planetary wellbeing as well.

5.4 Efficient scenario activity level, energy intensity and final demand

A summary assumptions, efficient technology and efficient UEC are given for lighting and appliances in the below table.

Table 12: Assumptions, efficient technology and efficient UEC for appliances

Appliances	Technology /efficiency	Diffusion in 2040 (%)	UEC (kWh/yr)
Incandescent lamps (8 hrs/day, 365 days/yr, four lamps/households)	55 W	0% share	642
CFLs (8 hrs/day, 365 days/yr, four lamps/households)	15 W	20% share	175
LED (8 hrs/day, 365 days/yr, four lamps/households)	7 W	80% share	81.76
Fans (12 hrs/day, 200 days/yr)	35 W (size of 1200 mm sweep)	153	84
TV (6 hrs/day, 365 days/yr)	Mix of technologies (LCD, LED), 33 W	114	72
Refrigerators	Direct cool (180-200 ltr) and Frost free (180-200 ltr)	100	250

5.4.1 Lighting

In 2040, final energy consumption from lighting end use in the efficient scenario will be around 1573 million kWh, or 2.4 times lower than the reference scenario level (Figure 19). Incandescent lamps are completely phased out and LEDs constitute 80% share of the total lighting end use in 2040.

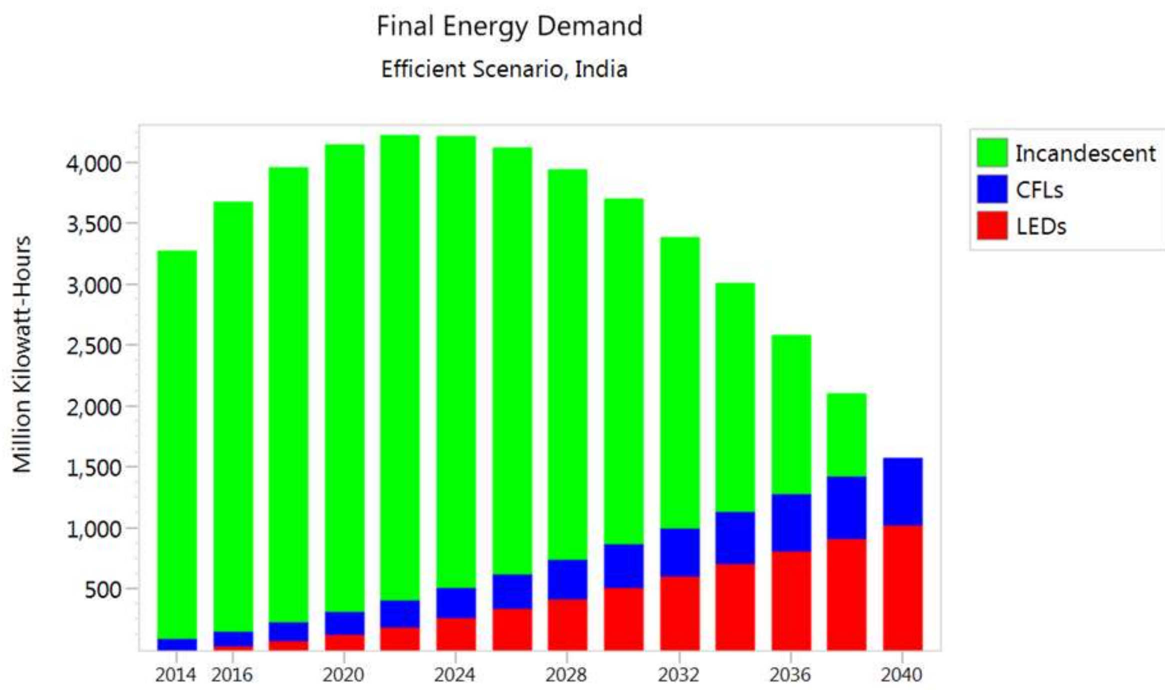

Figure 19: Lighting energy demand in the efficient scenario by 2040

5.4.2 Appliances

In 2040, final energy consumption from appliances end use in the efficient scenario will be around 7.2 billion kWh, or about two times lower than the reference scenario level (Figure 20). Energy consumption from refrigerators (3.9 billion kWh) is more than the energy consumption from fan and TV (2 and 1.3 billion kWh respectively) together in 2040. Efficient refrigerator energy consumption data for Indian subcontinent is taken from Bijli Bachao[4] portal, an initiative to help consumers make right decisions about their energy consumption. Appliances energy consumption is increasing rapidly among slum households even in the efficient scenario by about 4.5 times in 2040 compared to 2014. However compared to the reference scenario this growth in appliance energy consumption is less than half in the efficient scenario in 2040.

[4] https://www.bijlibachao.com/top-ten-appliances/what-are-best-refrigerator-fridge-lg-samsung-whirlpool-india.html

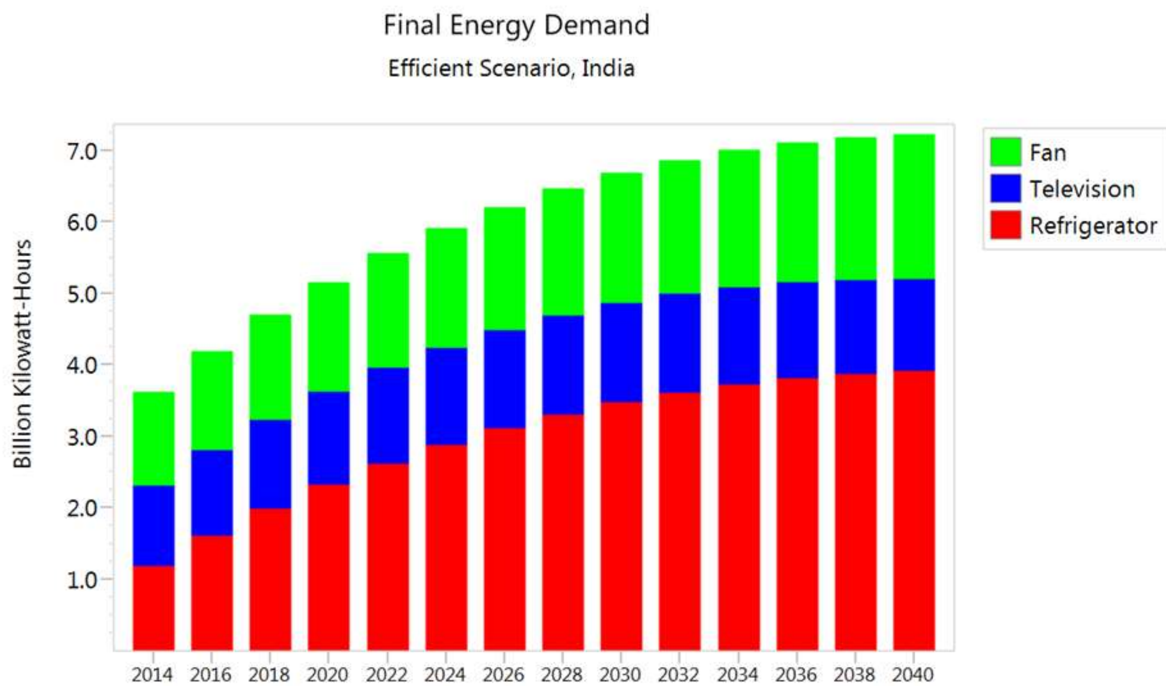

Figure 20: Appliances energy demand in the efficient scenario by 2040

5.4.3 Cooking

A summary assumptions, efficient technology and efficient UEC are given for cooking in the table 7 below.

Table 13: Assumptions, efficient technology and efficient UEC for cooking

	Diffusion in 2040 (%)	**Annual energy intensity/household**
Kerosene Stove	15	12 liter
LPG Stove	100	108 kg
Fuelwood Stove	10	240 kg
Coal/Charcoal Stove	4	24 kg

The annual energy intensity among slum households in 2040 reaches the current urban intensity i.e. 9 kg per household per month (Khandker, Barnes, and Samad, 2010, pp. 32). Fuelwood, kerosene, and charcoal stoves will still be used in the efficient scenario but with a lot less intensity compared to the reference scenario.

The final energy consumption for fuelwood, charcoal, kerosene, and LPG reaches to about 6, 0.4, 0.7, and 80 million gigajoules in the efficient scenario in 2040 (Figure 21). Significant fuel switching takes place from fuelwood to LPG.

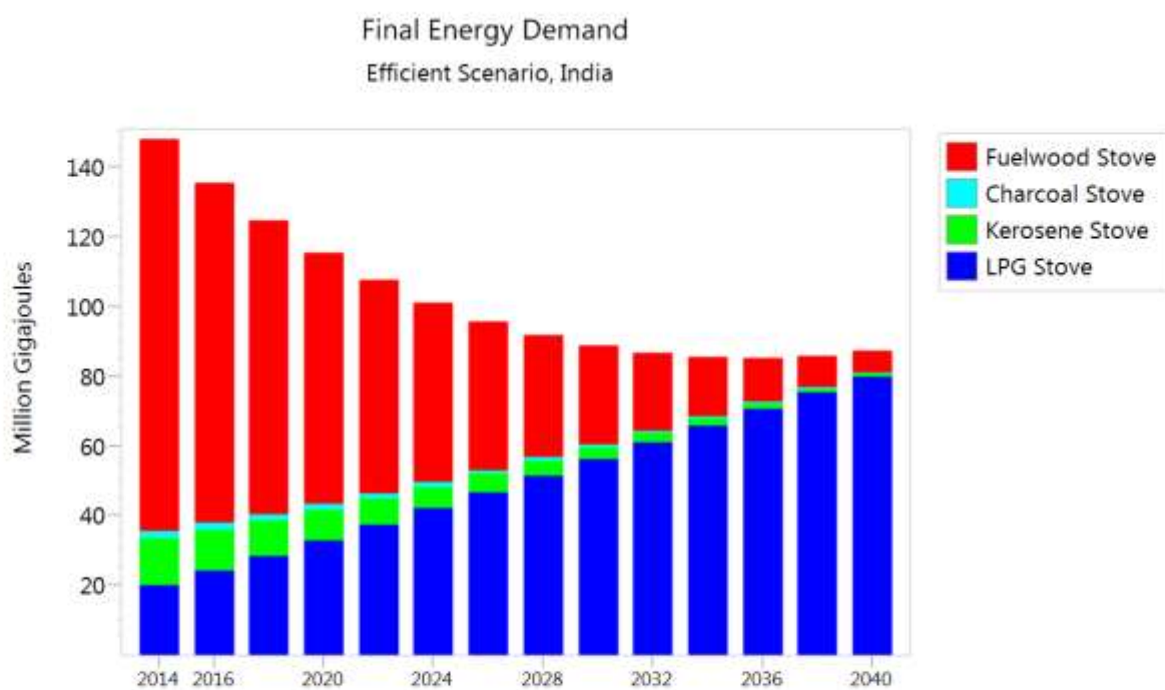

Figure 21: Cooking energy demand in the efficient scenario by 2040

Figure 22 shows that in 2014, overall final energy consumption in India was 48 billion kWh. Final energy consumption will decrease over the modelling period to 33 billion kWh in 2040 mainly because of fuel switching that takes place in the cooking and lighting end uses and the use of efficient appliances.

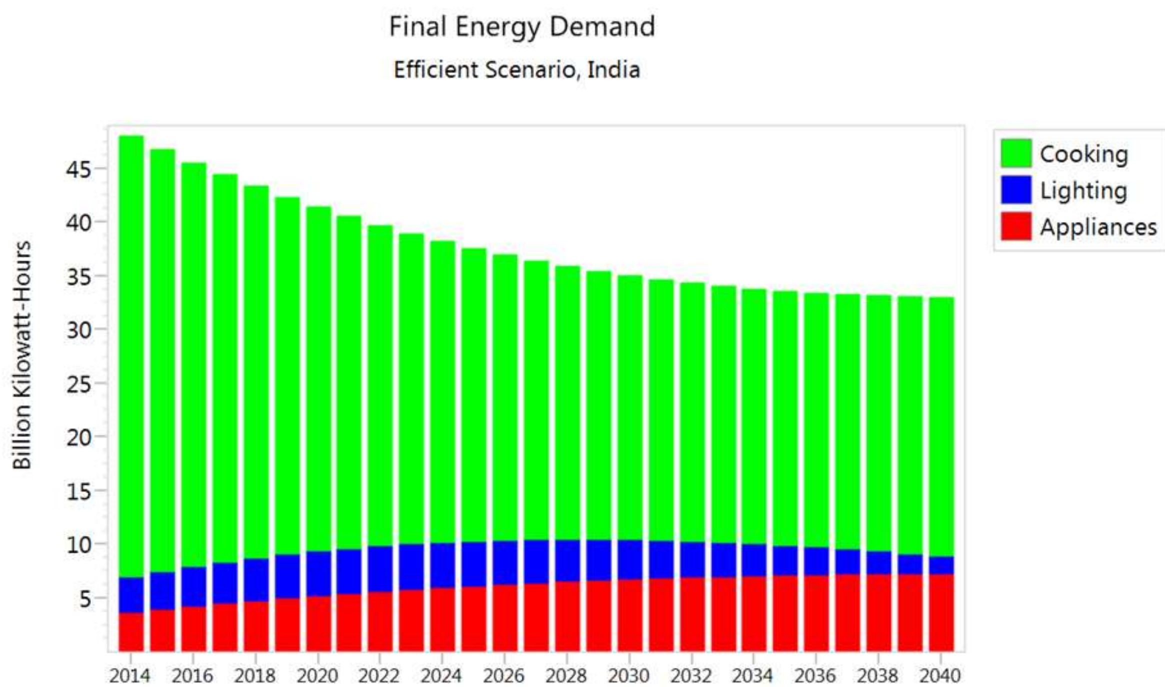

Figure 22: Final energy demand from all end uses in the efficient scenario by 2040

5.5 Energy savings (India)

The biggest final energy savings in 2040 are associated with appliances energy use which is roughly responsible for 55 percent total energy savings in India (Figure 23). Avoided energy consumption (energy savings) from all end uses is around 16.7 billion kWh, or 33 percent of the reference scenario consumption (~50 billion kWh) in 2040.

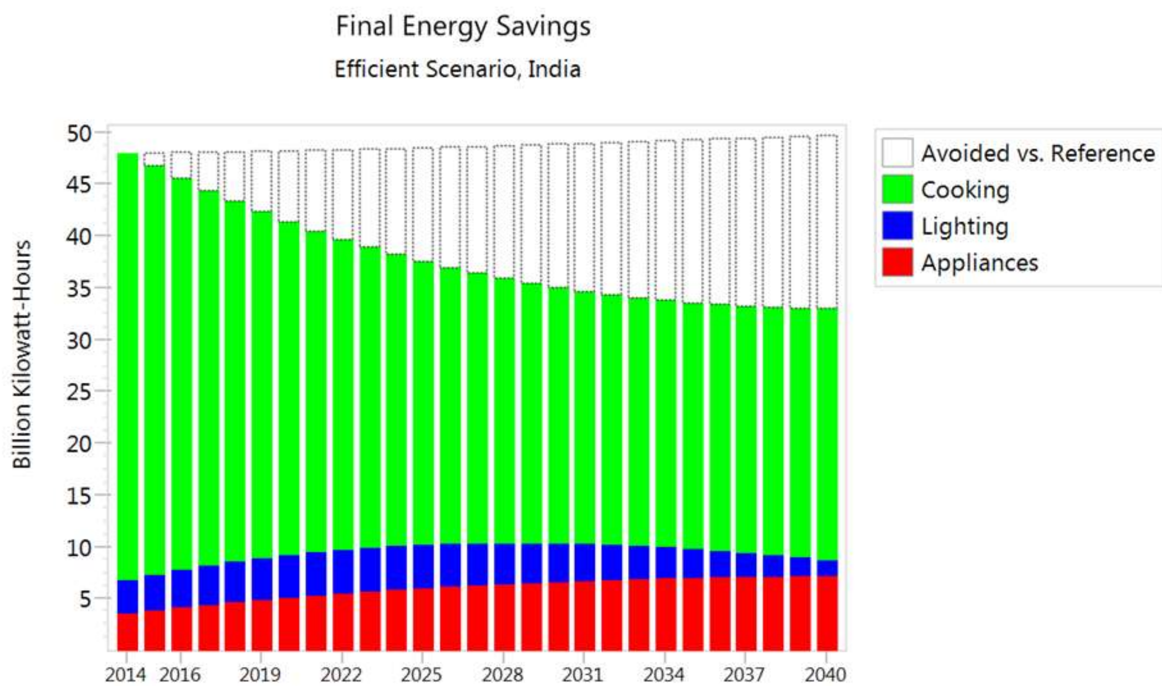

Figure 23: Energy savings (represented by Avoided vs. Reference) from realizing the efficient scenario

5.6 Overall energy demands from all regions

After investigating the analysis from the lens of a single country now overall energy demand of reference and efficient scenarios and energy savings from Sub-Saharan Africa and South Asia are given below. The two regions jointly are experiencing an increasing slum population growth at the rate of 1.67% per year.

5.6.1 Cooking

The slum household cooking energy-mix under the two scenarios as shown in Figures 24 & 25 indicates a gradual displacement of solid fuels by cleaner fuels. Under the efficient scenario, while there are increases over the reference case in the consumption of LPG, we notice a steady decline in the consumption of traditional biomass, charcoal, and kerosene. Fuelwood consumption per capita reduces from 1.67 GJ/cap in 2014 to 0.30 GJ/cap in the efficient scenario against 2.8 GJ/cap in the reference scenario in 2040. This becomes pertinent in the perspective that reduced fuelwood consumption is an important indicator for environmental sustainability under the efficient scenario. The observed reduction in total final energy requirement under the efficient scenario over the study period in Figure 25 is the result of a transition to more energy-efficient fuels for cooking using LPG. However there are countrywide differences where fuelwood consumption increases even in the efficient scenario nevertheless far less dramatic compared to the reference scenario.

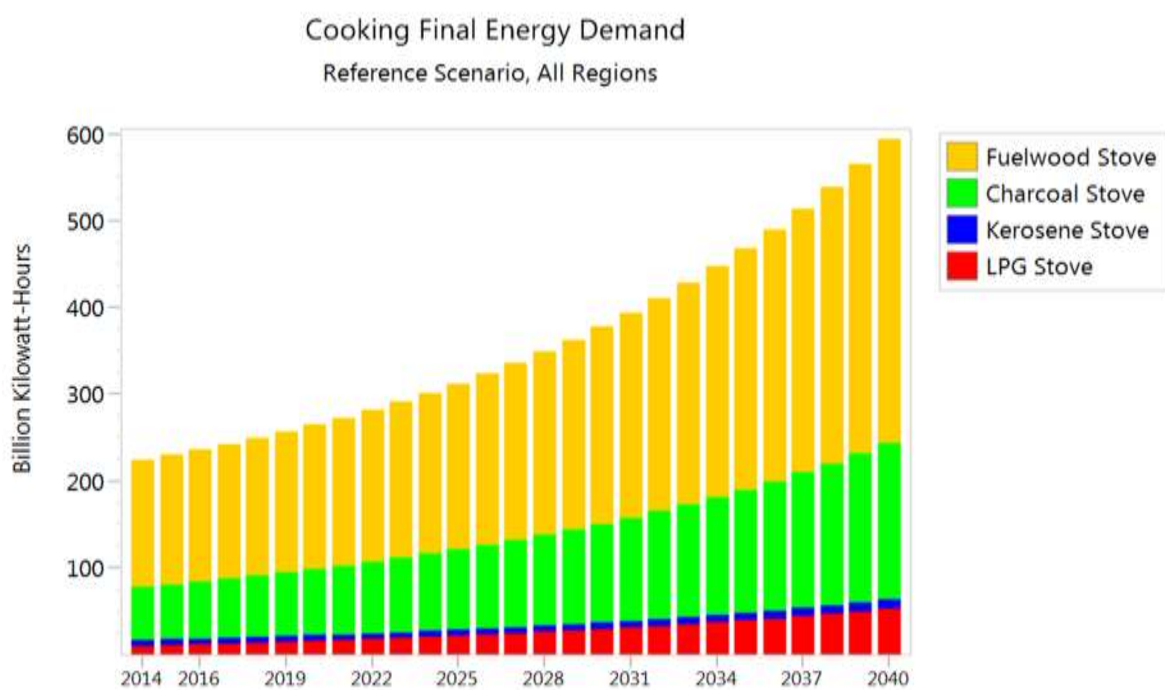

Figure 24: Final energy demand from cooking end use for all regions in the reference scenario by 2040

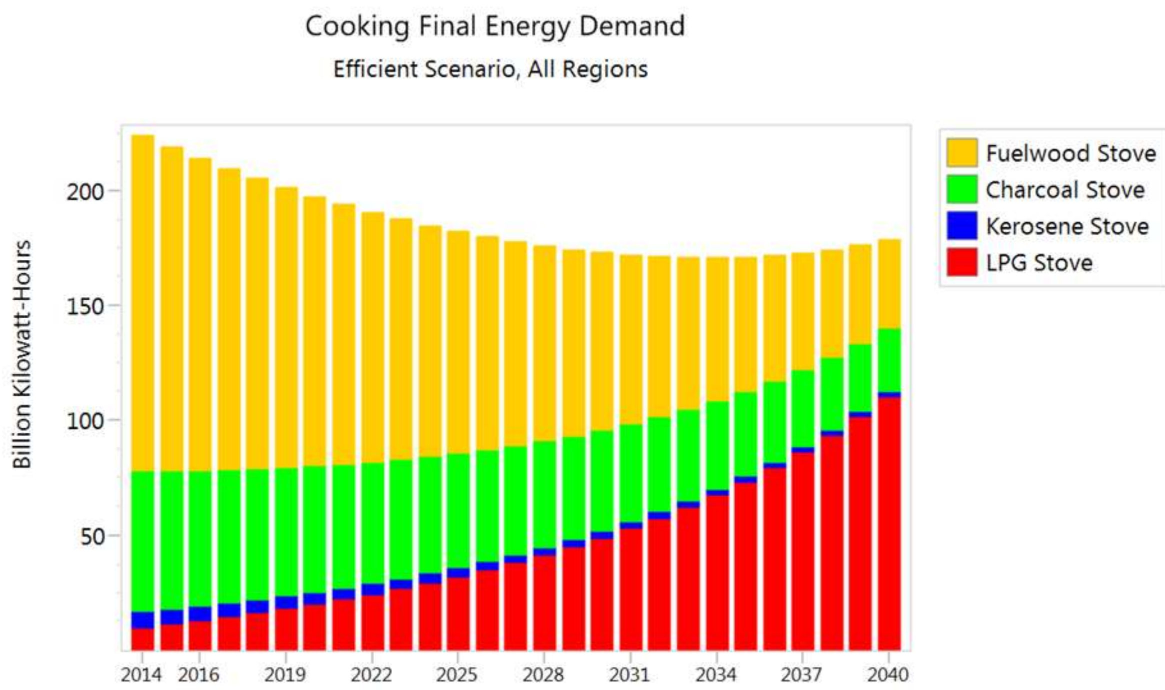

Figure 25: Final energy demand from cooking end use for all regions in the efficient scenario by 2040

5.6.2 Lighting

It is expected that despite widespread initiatives to promote efficient LEDs and CFLs, households will still be using incandescent lamps in 2040 in the reference scenario. The final energy consumption in the reference scenario reaches to 11.6, 9.5, and 1.5 billion kWh respectively for incandescent, CFLs, and LEDs in 2040 (Figure 26). It is noteworthy that although only 20% households use incandescent lamps in the reference scenario in 2040, energy consumption is still the highest. At the same time, final energy consumption in the efficient scenario reaches to 0, 3.2, and 5.9 billion kWh respectively for incandescent, CFLs, and LEDs in 2040 (Figure 27). Incandescent lamps are completely phased out in 2040 therefore they represent no energy consumption at the end of the scenario period.

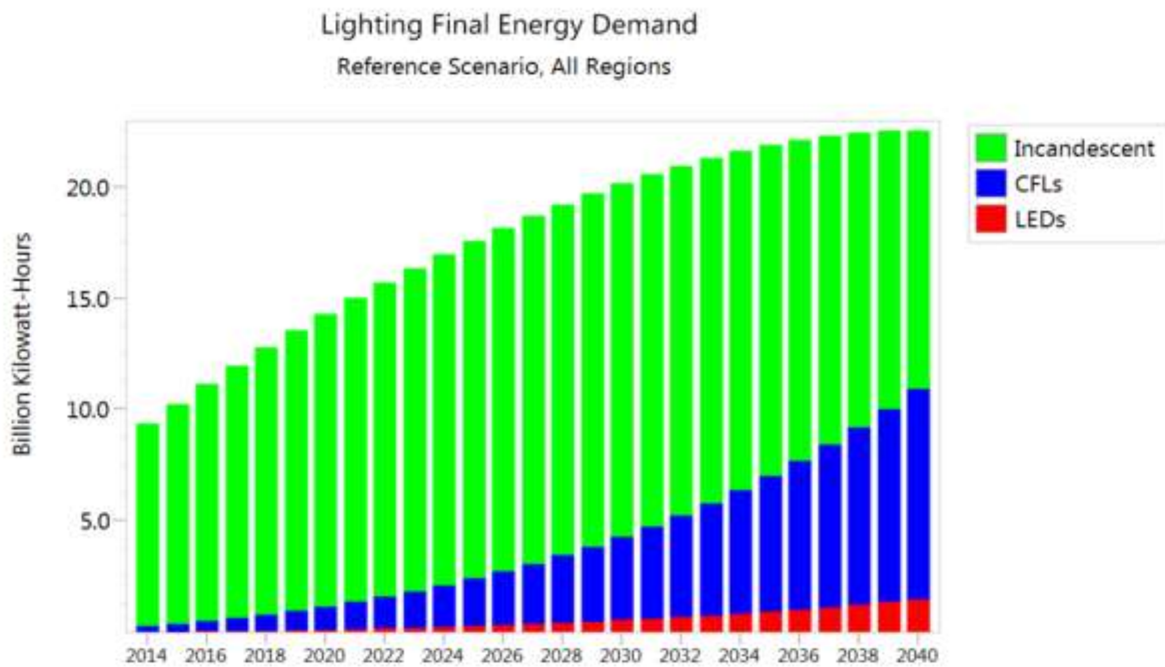

Figure 26: Final energy demand from lighting end use for all regions in the reference scenario by 2040

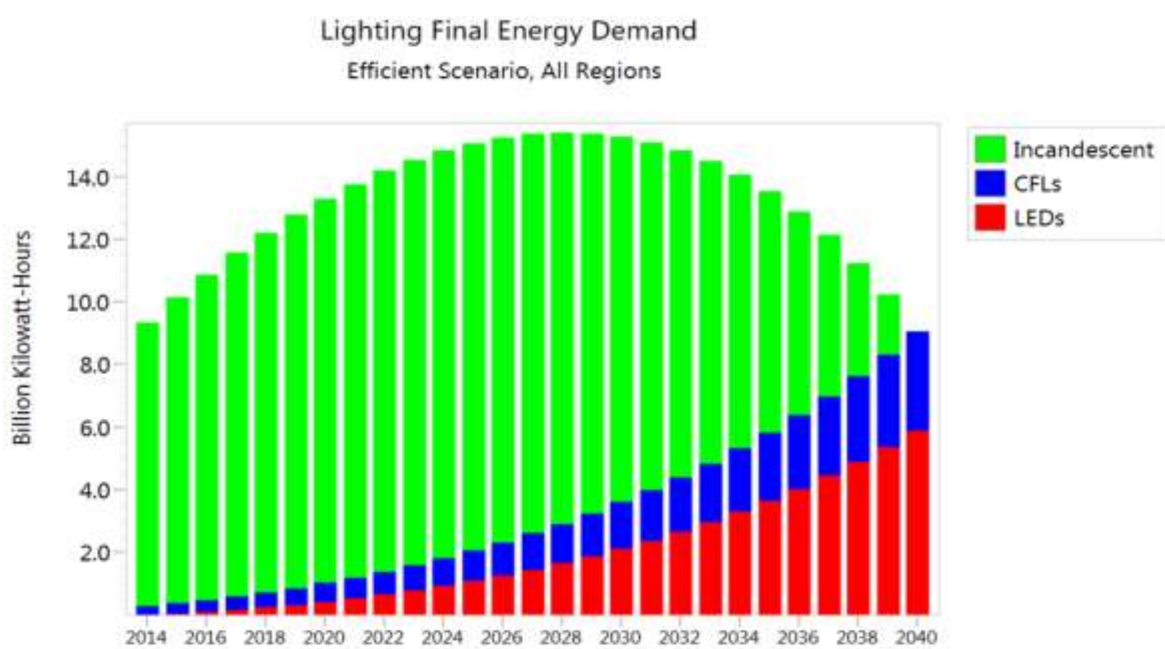

Figure 27: Final energy demand from lighting end use for all regions in the efficient scenario by 2040

5.6.3 Appliances

The final energy consumption for fan, TV, and refrigerator reaches to about 17, 18, and 53 billion kWh in 2040 jointly for SSA and SA in the reference scenario (Figure 28). At the same time, final energy consumption for fan, TV, and refrigerator reaches to about 8.3, 7.4, and 26.5 billion kWh in 2040 jointly for SSA and SA in the efficient scenario (Figure 29). SSA accounts for 63.6% (50.6 billion kWh) share of the total final energy consumption in the reference scenario in 2040 compared to roughly 67% (28 billion kWh) share in 2040 in the efficient scenario. Around 46 billion kWh energy is saved from slum household's switching to efficient appliances in the efficient scenario.

Energy consumption for appliances (fan, TV, and refrigerator) increases by 8.2 times in 2040 compared to 2014 in the reference scenario for SSA whereas 6.7 times jointly for the SSA and SA. This signals that the appliance growth in SSA is much higher than the two regions jointly. One of the reasons for this higher growth in SSA is that the region has suppressed demand in almost all end uses but more so in case of appliances also when compared with SA.

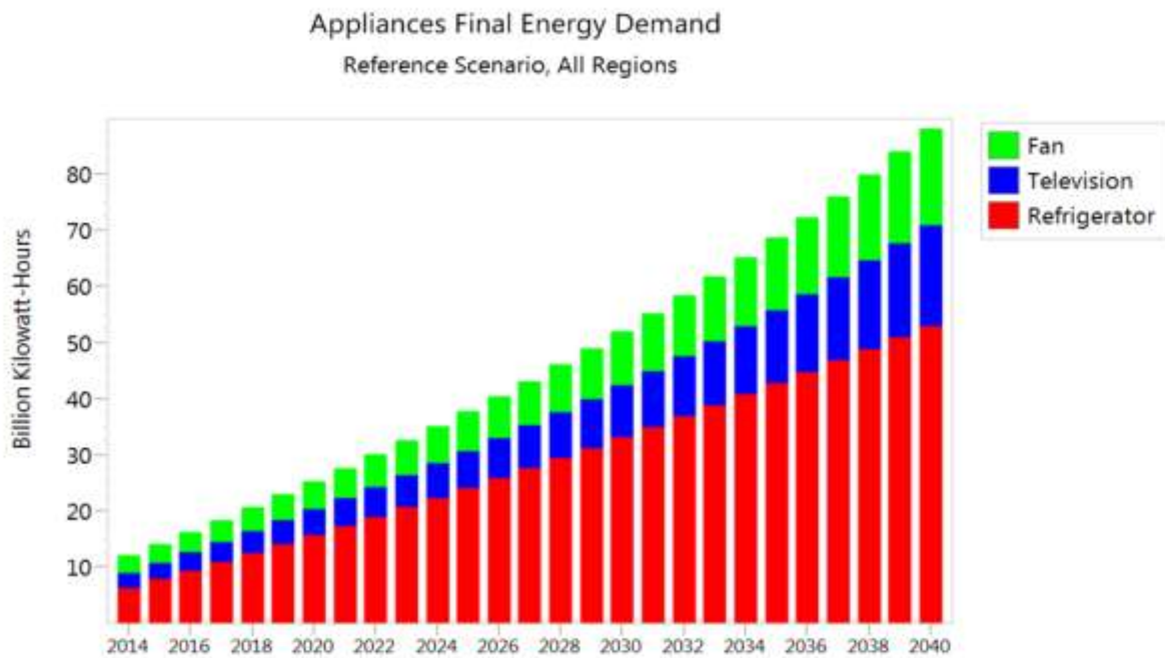

Figure 28: Final energy demand from appliances end use for all regions in the reference scenario by 2040

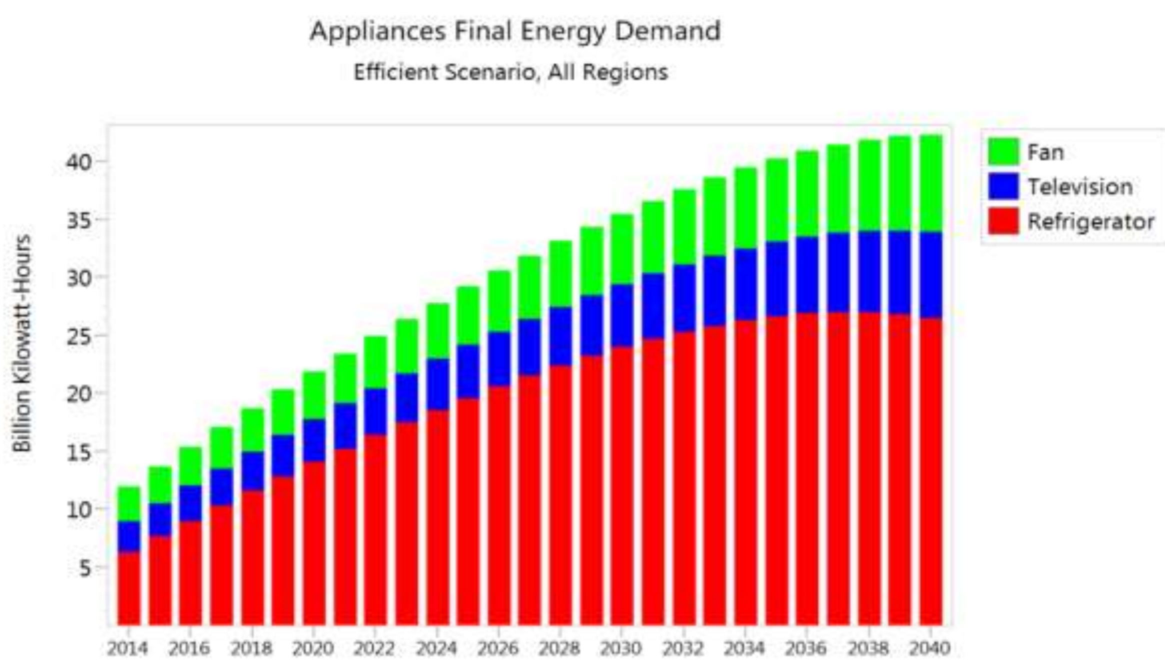

Figure 29: Final energy demand from appliances end use for all regions in the efficient scenario by 2040

5.6.4 Energy demand by end uses

Energy demand broken down by all energy end uses under the reference scenario and the efficient scenario is given in Figures 30 & 31 respectively. Final energy consumption in 2014 for all end uses was 245 billion kWh. Over the study period, the demand for energy is expected to increase by roughly 2.8 times in the reference scenario whereas remains about the same in the efficient scenario with increased energy services. In 2040 the energy demand in the reference scenario (700 billion kWh) will be 3 times larger than energy demand in the efficient scenario (230 billion kWh).

The figure 30 shows that, at present, cooking is responsible for the highest share of final energy consumption, and is further expected to grow in the future in the reference scenario. Overall, in 2040, cooking, appliances, and lighting will be responsible for roughly 84 percent, 13 percent and 3 percent of final energy consumption respectively.

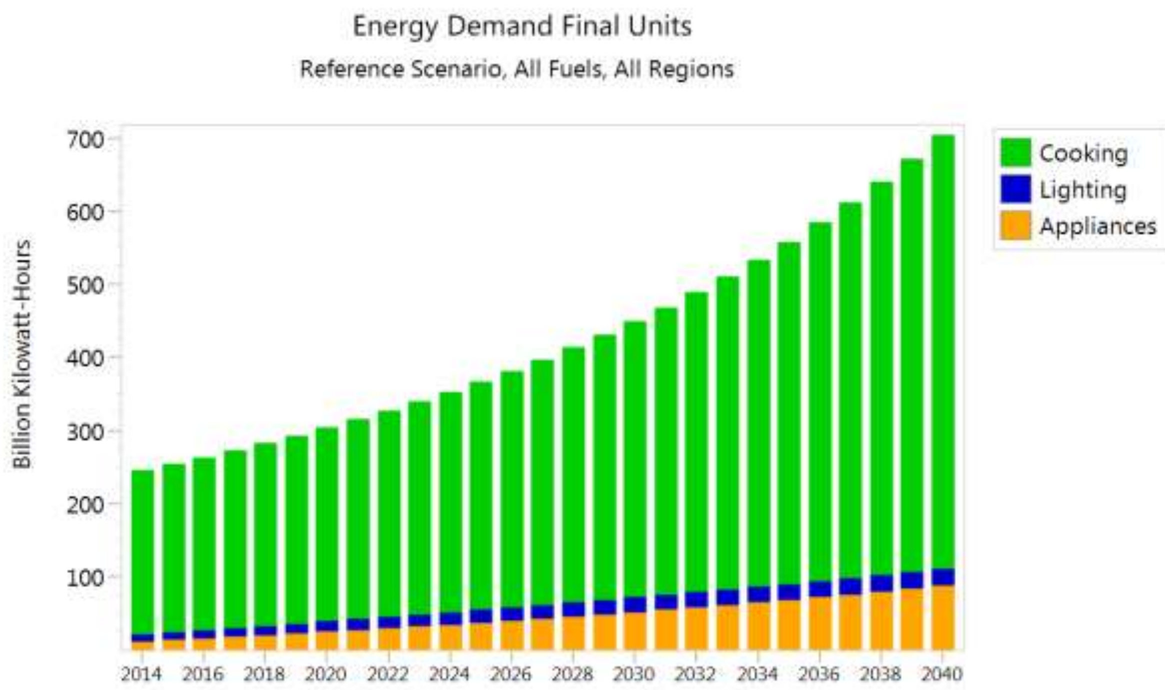

Figure 30: Final energy demand in the reference scenario from all regions by end uses

As is reflected by figure 30, the highest growth in energy demand in the reference scenario is observed in the cooking end use that mostly is comprised by biomass use. According to the World Bank and IEA projections, the consumption of biomass by Sub-Saharan African households will further increase in the next 30 years (World Bank 2011; IEA 2010).

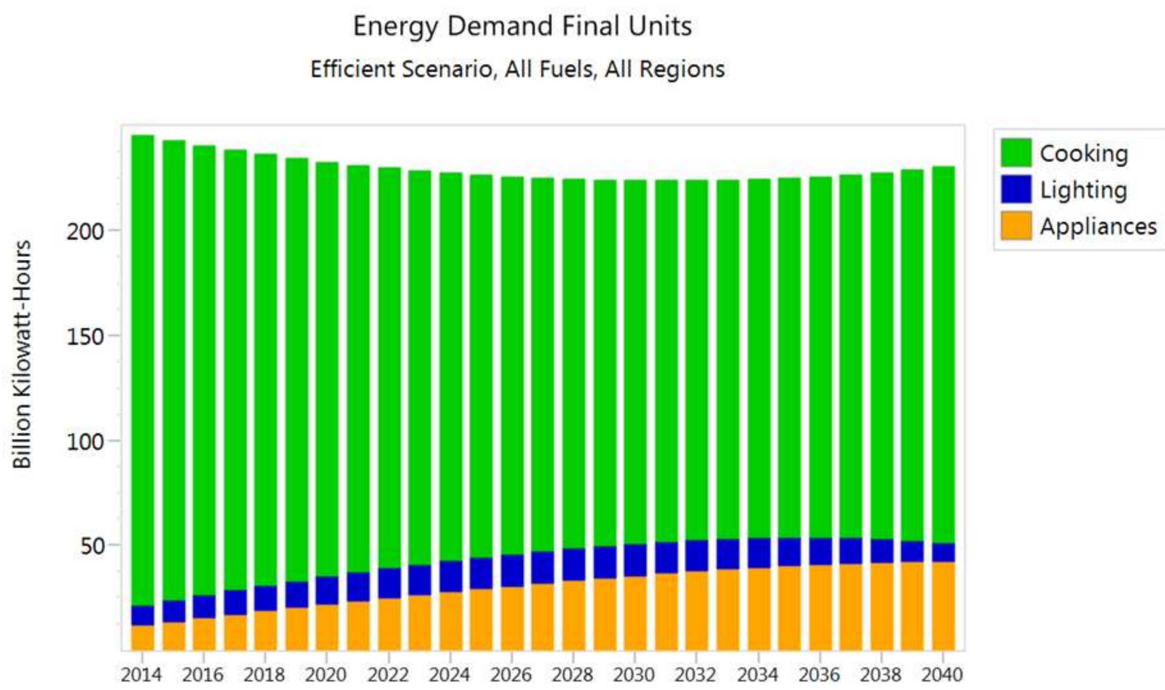

Figure 31: Final energy demand in the efficient scenario from all regions by end uses

As it is reflected in the figure 31, energy demand in the efficient scenario is offset by fuel switching that takes place from biomass based fuels to LPG. Therefore cooking energy demand does not increase with a greater degree compared to the base year, from 806 million Gigajoule (224 billion kWh) in the base year to only 644 million Gigajoule (179 billion kWh) in 2040.

Energy consumption in the reference and efficient scenarios by end-uses are given in the Table 14 & 15 respectively. The growth rate of the energy consumption in the reference scenario is 6.8% whereas it is almost 0% in the efficient scenario. This is remarkable that although energy services increased in the efficient scenario but the growth in energy consumption does not register.

Table 14: Energy consumption in the reference scenario in Billion Kilowatt-Hours (in selected years)

End uses	2015	2020	2025	2030	2035	2040
Cooking	230	264	311	377	468	594
Lighting	10	14	18	20	22	22
Appliances	14	25	38	52	69	88
Total	254	303	366	449	558	704

Table 15: Energy consumption in the efficient scenario in Billion Kilowatt-Hours (in selected years)

End uses	2015	2020	2025	2030	2035	2040
Cooking	219	197	182	173	171	179
Lighting	10	13	15	15	14	9
Appliances	14	22	29	35	40	42
Total	243	233	226	224	225	230

Cumulative energy demands over the study horizon decreases by about 1.8 times (180%) under the efficient scenario compared to reference scenario (i.e. 11452 bkWh in the reference scenario against 6192 bkWh in the efficient scenario). The aggregate per capita slum household electricity consumption would increase from 67 kWh/cap in 2014 to 114 kWh/cap in 2040 under the efficient scenario, compared with the 245 kWh/cap under the reference scenario in 2040.

5.6.5 Energy demand by energy sources

Figure 32 presents final energy consumption by energy sources in the reference scenario. In 2014, it comprised 60 percent biomass (fuelwood), 25 percent charcoal, 9 percent electricity, 3 percent kerosene and 4 percent LPG. The figure shows that the energy demand on aggregate level is rapidly growing from all end uses in the reference scenario. Energy demand from biomass, charcoal, LPG, Kerosene, and electricity will increase by around 2.2, 2.5, 3.1, 1.4, and 3.1 percent per year during 2015–2040 respectively in the reference scenario. A large share of energy demand for cooking is currently addressed by fuelwood and charcoal. Due to the penetration of more efficient and convenient LPG stoves, a fuel switch will take place for cooking nevertheless more pronounced in the efficient scenario (Figure 33) compared to the reference scenario.

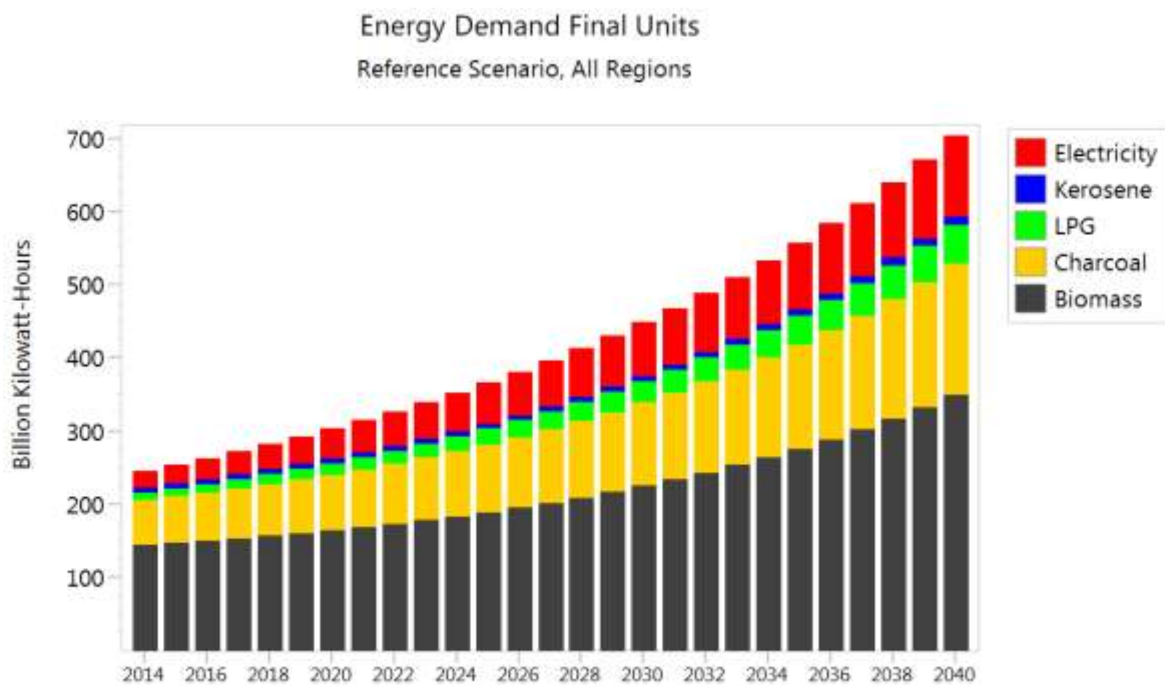

Figure 32: Final energy consumption by energy sources in the reference scenario

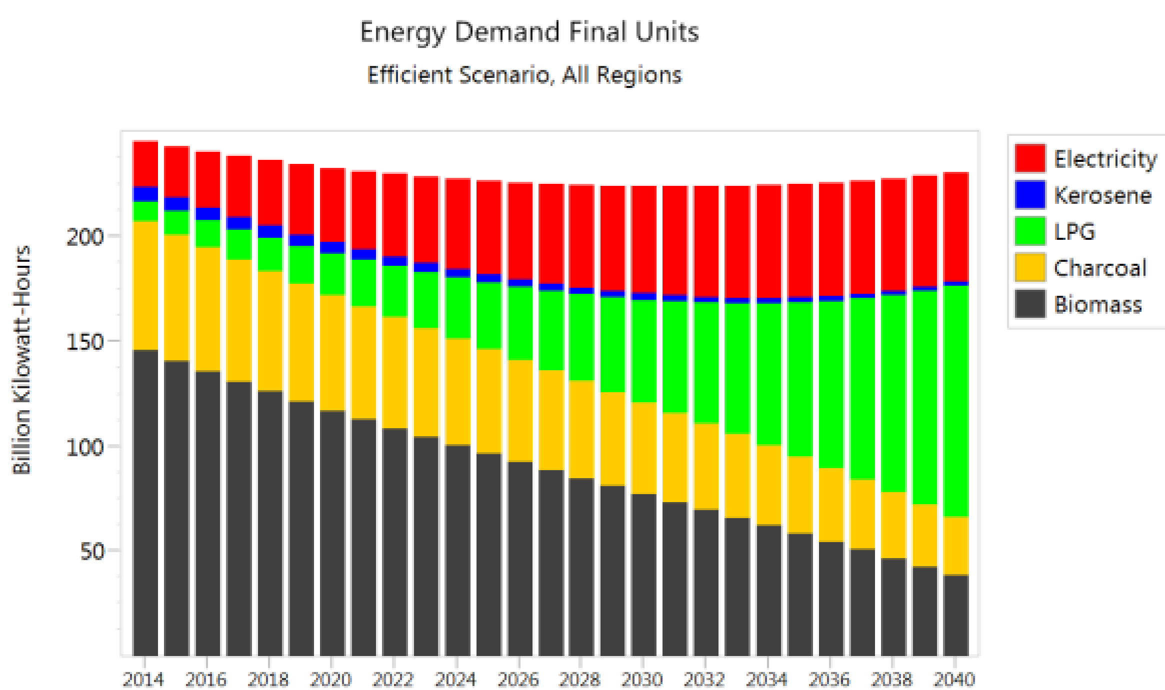

Figure 33: Final energy consumption by energy sources in the efficient scenario

5.8 Overall final energy savings

The biggest final energy savings are associated with fuel switching from biomass and charcoal to LPG, as presented in Figure 34. Avoided electricity consumption is around 59 billion kWh, or roughly 53 percent of the reference consumption (110 billion kWh) in 2040.

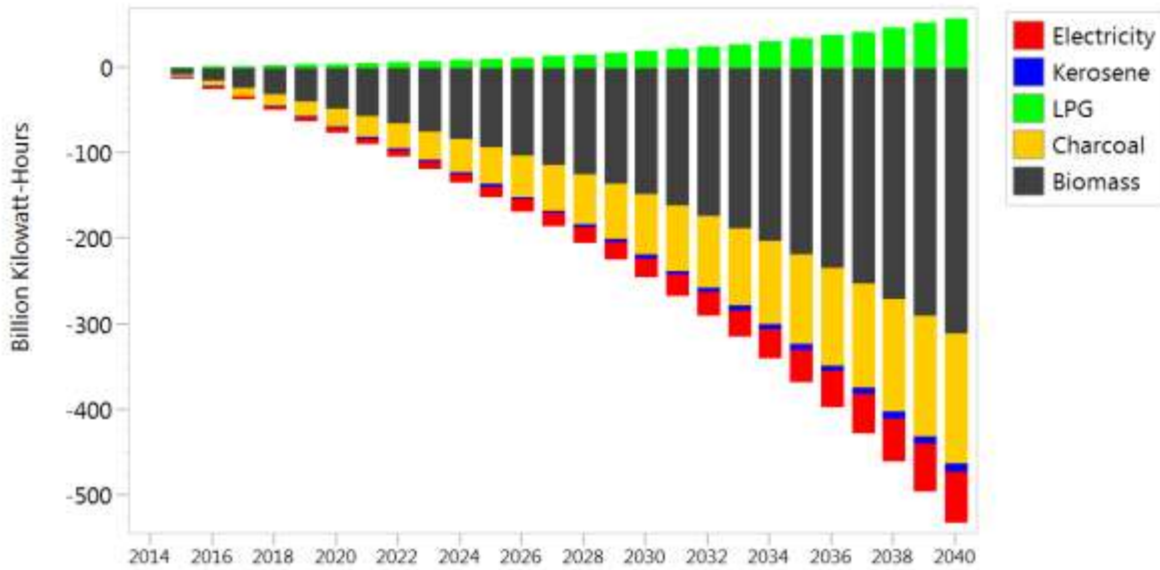

Figure 34: Final energy savings by energy source for all regions in the efficient scenario vs. the reference scenario, 2014-2040

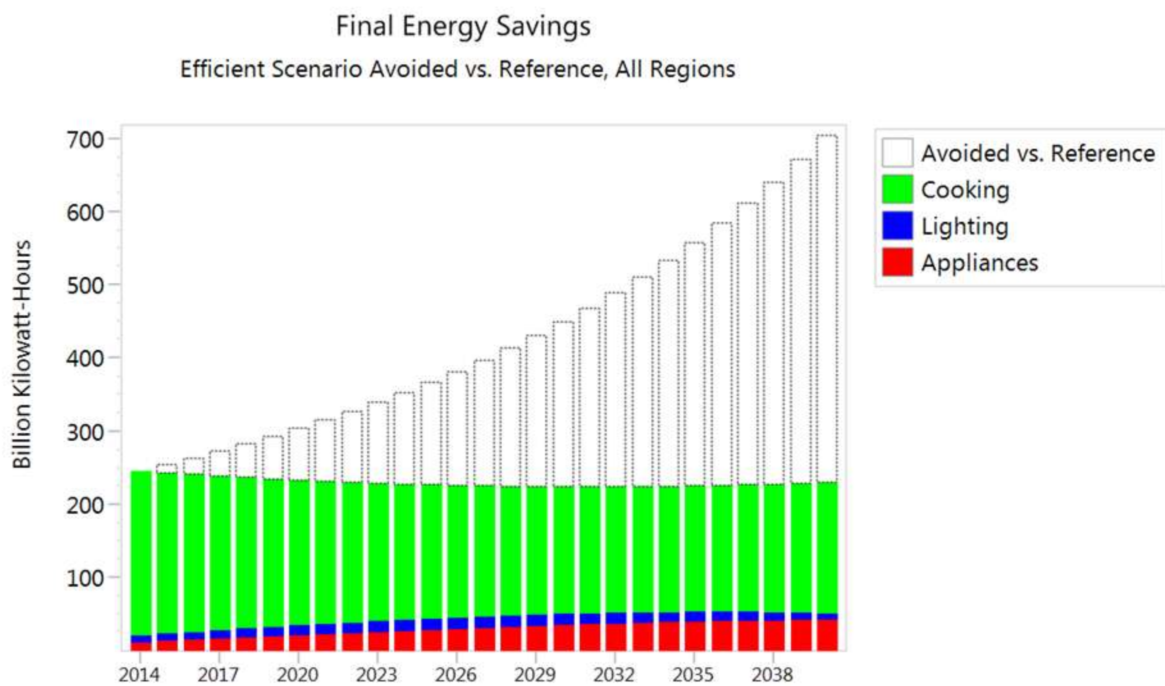

Figure 35: Final energy savings (represented by Avoided vs. Reference) from realizing the efficient scenario in the selected years

Energy savings from all regions in 2040 by transitioning of energy uses to efficient scenario is 474 billion kWh (Figure 35; Table 16). Overall about 67% energy savings can be achieved in 2040 from all end-uses and energy sources in the study regions. It is striking that about 87% of total energy savings come from fuel switching that takes place in the cooking end use whereas about 10% and 3% energy savings arise from appliances and lighting end uses. This reflects the importance of cooking end-use in slum households' context in the years to come. Within the appliance end use, the highest share of energy saving in 2040 comes from refrigerator (57%) while savings from fan and TV are about the same (20% and 23% respectively).

Table 16: Energy savings in Billion Kilowatt-Hours (in selected years)

End uses	2015	2020	2025	2030	2035	2040
Cooking	-11	-66	-129	-204	-297	-415
Lighting	-0	-1	-2	-5	-8	-13
Appliances	-0	-3	-8	-16	-28	-46
Total	**-11**	**-71**	**-140**	**-225**	**-333**	**-474**

At the same time, the total cumulative energy demand between 2014-2040 in the reference scenario is 11452 Billion Kilowatt-Hours from all end uses while the total cumulative energy demand in the efficient scenario is 6192 Billion Kilowatt-Hours. Therefore a total cumulative energy savings of 5260 Billion Kilowatt-Hours can be realized between 2014-2040 by switching to the efficient scenario (Table 17). Whereas in 2040 the total energy consumption is about 704 billion kWh in the reference scenario compared to 230 billion kWh in the efficient scenario.

Table 17: Total (cumulative) energy savings in Billion Kilowatt-Hours until 2040

End Use	Until 2040
Cooking	4725
Lighting	121
Appliances	414
Total	**5260**

To put the total (cumulative) energy savings figure into a context, in 2014 United States generated about 4093 billion kWh of net electricity (EIA 2015). However as reflected above about 87% of total energy savings in this analysis are coming from the cooking end use that is mainly comprised of biomass and LPG. Energy savings that are coming from electricity (lighting and appliances) are only 535 billion kWh which is about seven times less compared to one year's electricity generation from the United States. Cumulatively efficient scenario uses 46% less energy compared to the reference scenario by 2040 while all basic energy services are fully met. Also, Energy consumption in 2040 in the reference scenario increases by 2.8 times while almost remains the same in the efficient scenario compared to the base year.

Electricity demand per household in the base year from all regions from this research is 300 kWh ~ 67 kWh per person. Further, World Energy Outlook (WEO) assumes an initial threshold level of electricity consumption for urban household to be 500 kWh per year (IEA 2012). This threshold is for average urban population hence 300kWh electricity consumption coming from this research is a reasonable figure to represent slum household's electricity consumption from SSA and SA. This average electricity consumption is very small when contrast to worldwide per capita annual average of 2,600 kWh (WEO 2011) which include energy consumption from all areas and not just household level.

5.9 Conclusion

In this chapter I have estimated the current level of end-use demand, forecasted growth in slums energy demand until 2040 by end-uses in the reference and efficient scenarios. Energy savings are estimated by comparing the two scenarios. First, a description of detailed energy savings analysis conducted in LEAP is presented by India example. Later, overall energy savings analysis is given for all the regions.

Energy savings from all the regions in 2040 by transitioning of energy uses to efficient scenario is 474 billion kWh. Results suggest that overall about 67% energy savings can be achieved in 2040 from all end-uses and energy sources compared to the reference scenario. Cumulatively 46% energy savings (5260 Billion Kilowatt-Hours) can be achieved in the study period from the efficient scenario while all basic energy needs are fully met.

About 87% of total energy savings come from fuel switching that takes place in the cooking end use whereas about 10% and 3% energy savings arise from appliances and lighting end uses in 2040. Energy savings by achieving the efficient scenario from individual end-uses compared to reference scenario in 2040 are - cooking: 70% (415 billion kWh), lighting: 59% (13 billion kWh), and appliances: 52% (46 billion kWh). However, energy consumption from LPG increases by about 50% (58 billion kWh) compared to reference scenario while consumption from biomass is reduced by 87% (464 billion kWh) in 2040.

Energy savings by realizing the efficient scenario from individual appliances compared to the reference scenario in 2040 are – Fan: 51% (9 billion kWh), TV: 60% (10.6 billion kWh), and Refrigerator: 50% (26.5 billion kWh). Energy consumption in 2040 in the reference scenario increases by 280% compared to the base year and remains almost the same in the efficient scenario while basic energy needs are full met. One of the interesting results are that although for some countries such as India, the growth rate in slum population is decreasing, however the energy consumption is still increasing mainly due to increase in diffusion or ownership of end-uses and their intensive use as well.

Chapter 6: Greenhouse gas emissions reduction potential

In the context of rapid urbanization and increasing number of slum households it is a pertinent question to find out how large are the GHG emissions reduction potential of achieving the efficient scenario. This chapter details the calculation method of GHG emissions, provide estimates of the emissions in the reference and the efficient scenario, and emissions reduction potential lie in the efficient scenario. I also select few countries from the study regions to show their emission trajectories based on how their slum population, appliance diffusion, and unit energy consumption grow over the study period.

6.1 Calculation method of GHG emissions

Below I provide the calculation method of GHG emissions in the Reference and Efficient scenarios using LEAP's carbon emissions factors for countries. Comparing the GHG emissions from the reference and the efficient scenarios provide the magnitude of the GHG reduction potential as a contribution to climate change problem from slum households' transition towards more energy efficient energy use.

Calculation of GHG mitigation from final energy savings:

$$\Delta GHG(y) = \Delta E(y) \times f_c(y)$$

GHG(y) = CO_2e mitigation in year y

E(y) = Final energy savings in year y

fc = Carbon conversion factor (kg/kWh or kg/GJ) in year y

Avoided carbon emissions are important from climate change perspectives however energy savings have direct benefits in improving slum dwellers socio-economic condition. At the same time, poor people are more severely affected by the impact of climate change compared to normal urban households. It is important to know how large are the GHG emissions reduction potential of slums transition to efficient energy systems so that policies can be designed which are aligned with low emission slum development pathways. This will provide a framework for mitigation within development context or development within mitigation framework.

Environmental loadings in LEAP represent the GHG and other pollutants that are emitted by energy demand technologies. Each environmental loading is listed as an effect (i.e. GHG emissions per unit of energy used) which is lower level branches below demand technologies. In order to use LEAP to estimate the emissions of main pollutants in the reference and efficient scenarios, links are created between relevant technology branch and matching technologies from the Technology and Environmental Database (TED). TED offers wide information that describes technical characteristics, and environmental impacts of a broad range of energy technologies. TED includes a rich library of emission factors of energy using and producing technologies which also includes default emission factors provided by Intergovernmental Panel on Climate Change (IPCC) generally used by national communication for climate change mitigation analysis (Heaps 2017). However, emission factors can also be added manually. In few cases where IPCC tier 1 technology does not have an entry for the fuel, the closest similar entry is chosen, for example, the IPCC 'oil residential' entry can be linked to the 'Kerosene Stove' LEAP category. LEAP multiplies the loadings defined by the analyst by the total energy used in each year of reference and efficient scenarios.

To account for emissions, LEAP uses a territorial accounting approach similar to that which is used by IPCC and UNFCCC for preparing National GHG Emissions Inventory Guidelines. As per this approach, fugitive and combustion emissions which occur in the study area are included. The same method is implemented for all countries with respective data. IPCC recommends using Fourth Assessment report (AR4) for Global Warming Potential (GWP) values for national communications to the UNFCCC. Therefore GWP values from the AR4 for each greenhouse gas are used in the analysis. The GWP values measure the warming potential of a tonne of each gas relative to a tonne of CO_2.

Environmental impacts of end-use devices that consume electricity come upstream for example from power plants that produces the electricity, and therefore the carbon profile of each country's electricity generation is different. The electricity emission factor data (for devices that use electricity) are taken for each country from International Energy Agency (IEA). The electricity emission factors are representative of the average power mix for a given country.

Emission factors suggested by the Intergovernmental Panel on Climate Change (IPCC) Tier 1 default technology are used for cooking end-uses (fuelwood, charcoal, kerosene, and LPG). Fuelwood and charcoal release biogenic CO_2. According to IPCC guidelines, biogenic CO_2 emissions are compensated by the CO_2 captured during the growing period of the biomass, in that sense the emissions from biomass are neutral. Therefore GWP from biogenic emissions will be zero. The assumption is that the emissions from fuelwood and charcoal are considered part of the carbon cycle. However non-biogenic effects (CH_4, CO, NO, NO_2, NMVOCs etc) are assigned to the emissions coming from fuelwood and charcoal stoves which are shown in the GWP values.

6.2 Overall GHG emissions

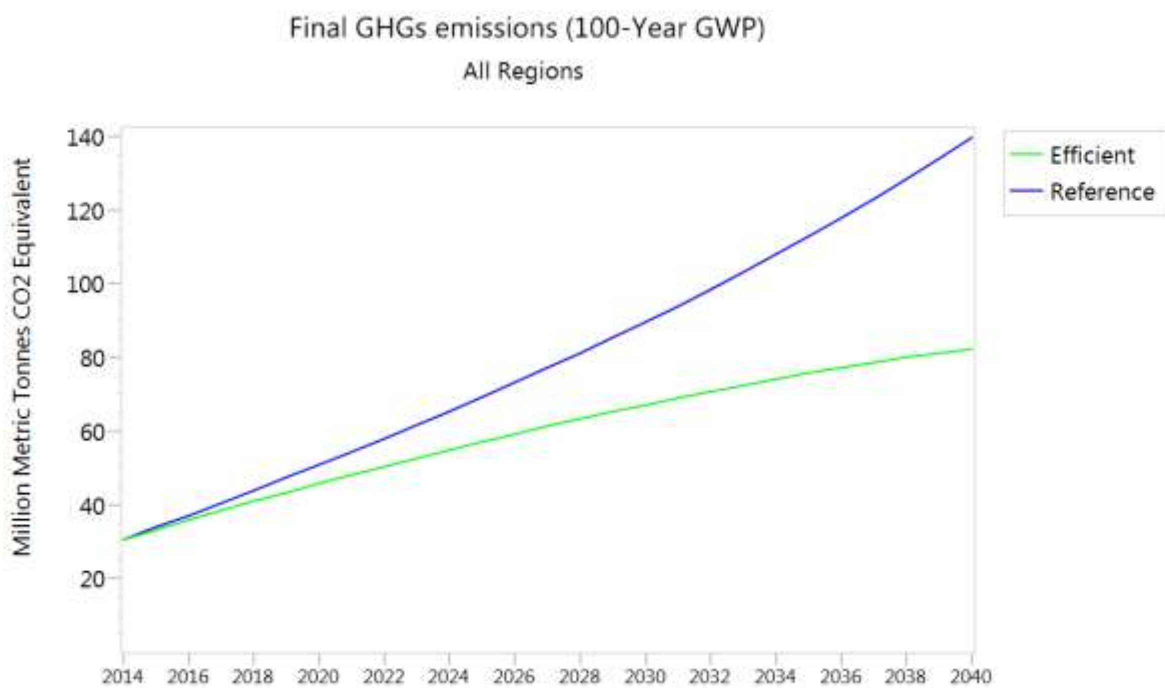

Figure 36: Final GHG emissions (CO_2 Equivalent) for all regions in the reference and efficient scenarios

As per Figure 36, household GHG emissions grew from 31 million tonnes CO_2 eq. (100 kg per capita) in 2014 to 82 million tonnes CO_2 eq. (183 kg/capita) and 140 million tonnes CO_2 eq. (311 kg/capita) under the efficient scenario and reference scenarios respectively by 2040. Therefore, a total reduction of 58 million tonnes GHG emissions are realized by the efficient scenario in 2040. These findings are supported by the study of Ibitoye (2013) who analyzed the household energy requirements in Nigeria under reference and MDG scenarios. He found that under the

MDG scenario CO_2 emissions grew from 73 kg per capita in 2005 to 181 kg/capita by 2020 which is similar to my findings as well. As per the World Bank 2013 data, an average person in SA and SSA emits 1.4 and 0.8 tonnes CO_2 eq. respectively. Therefore, when contrasted with national and global emissions reported in international reports (World Bank 2013, UNDP 2007), it can be securely said that meeting the slum households' energy needs through efficient energy systems only contribute a tiny proportion of global emissions. At the same time, average U.S. and the world emissions are 16 and 5 tonnes per capita CO_2 eq. which further illustrates the miniscule nature of emissions coming from the slums.

The impact of energy use on non-biogenic slum households' CO_2 emissions under the reference and efficient scenarios is provided in the Figure 37. Overall, there is a 22% decrease in cumulative non-biogenic household CO_2 emissions under the efficient scenario over the entire study horizon compared to the reference scenario. Household non-biogenic CO_2 emissions grew from 25 million tonnes in 2014 to 80 million tonnes and 127 million tonnes under the efficient scenario and reference scenarios respectively by 2040. Therefore a total reduction of 47 million tonnes non-biogenic CO_2 emissions are realized by the efficient scenario in 2040 from switching to the LEDs and CFLs and use of more efficient appliances in the efficient scenario.

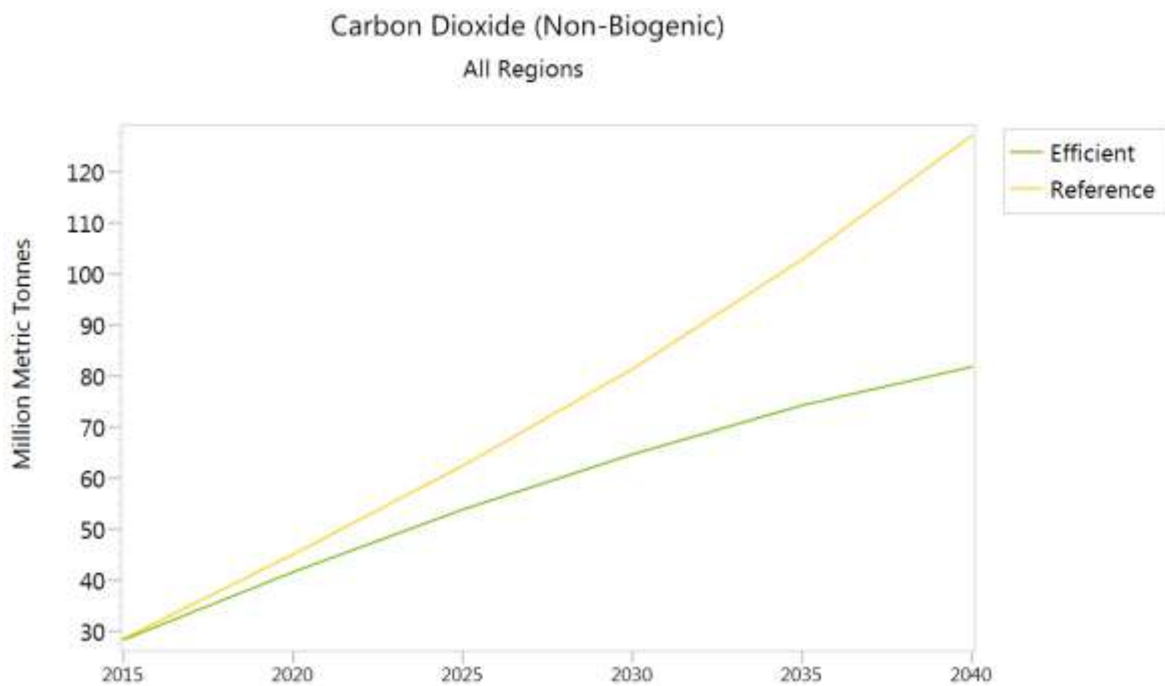

Figure 37: Carbon dioxide emissions (non-biogenic) in the reference and efficient scenarios for all Regions

6.3 Emission trajectories of few individual countries as examples

Every country in the study region has their own specific emission trajectories based on how their slum population and energy consumption grow. Due to this reason it is worth looking the emission trajectories of few individual countries in the sub-Saharan Africa and South Asia. Here, for example, I provide a description of the analysis of carbon dioxide emissions of slums from the realization of efficient scenario as compared to the reference scenario for India, Kenya, and Bangladesh. The figure 38 below presents the impact of energy use on non-biogenic carbon dioxide emissions in the reference and efficient scenarios in India.

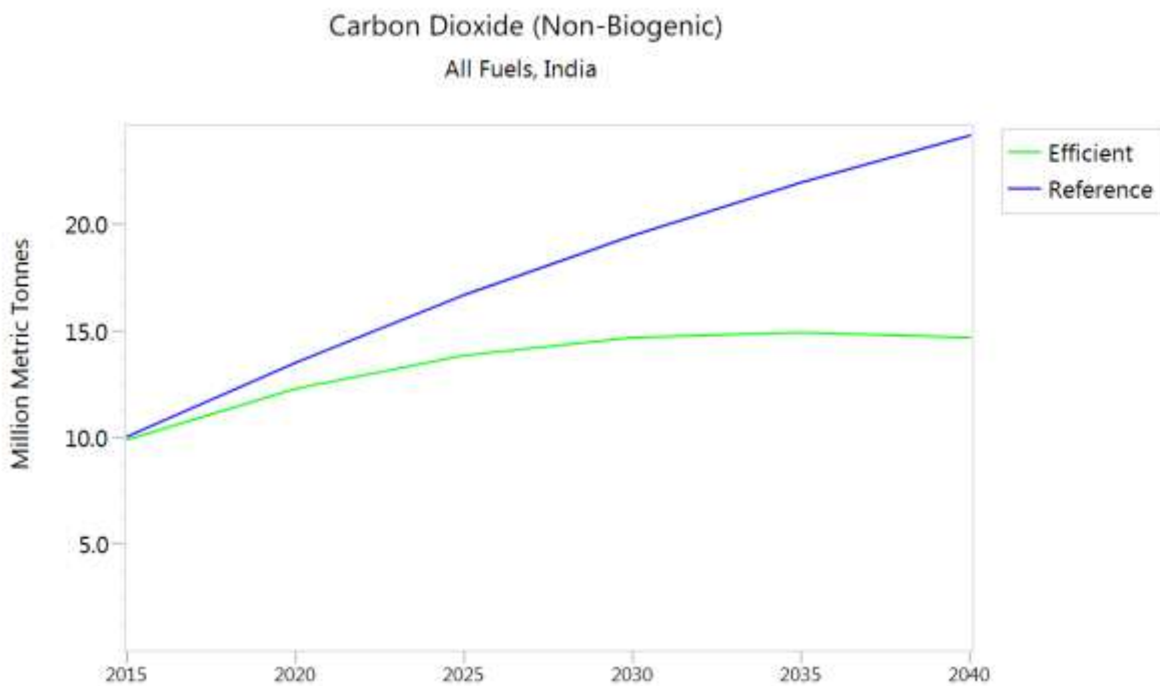

Figure 38: Carbon dioxide emissions (non-biogenic) in the reference and efficient scenarios for India

To calibrate the emission results I have used a study from The Gold Standard Foundation (2014) that looked at CO_2 emissions released from urban poor households in Delhi, India. They found that each urban poor household contributes around 2.41 metric tonne CO_2 per year in Delhi. They came up with this number by accounting all sources of GHG from residential and community energy uses (water supply, sanitation and wastewater, MSW disposal, transportation) attributed to each household. In this research, I have found that slum households from India release about a total of 10 million metric tonne CO_2e in the base year. This emission is distributed amongst 22 million slum households in the base year and therefore the emission comes as 0.46 metric tonne per household. To explain the lower emission coming from my analysis compared with The Gold Standard Foundation study is because I do not account for community energy services attributed to each household and there are numerous cities where slum households are living even a less emission intensive lifestyle than Delhi, one of the largest metropolitan in India.

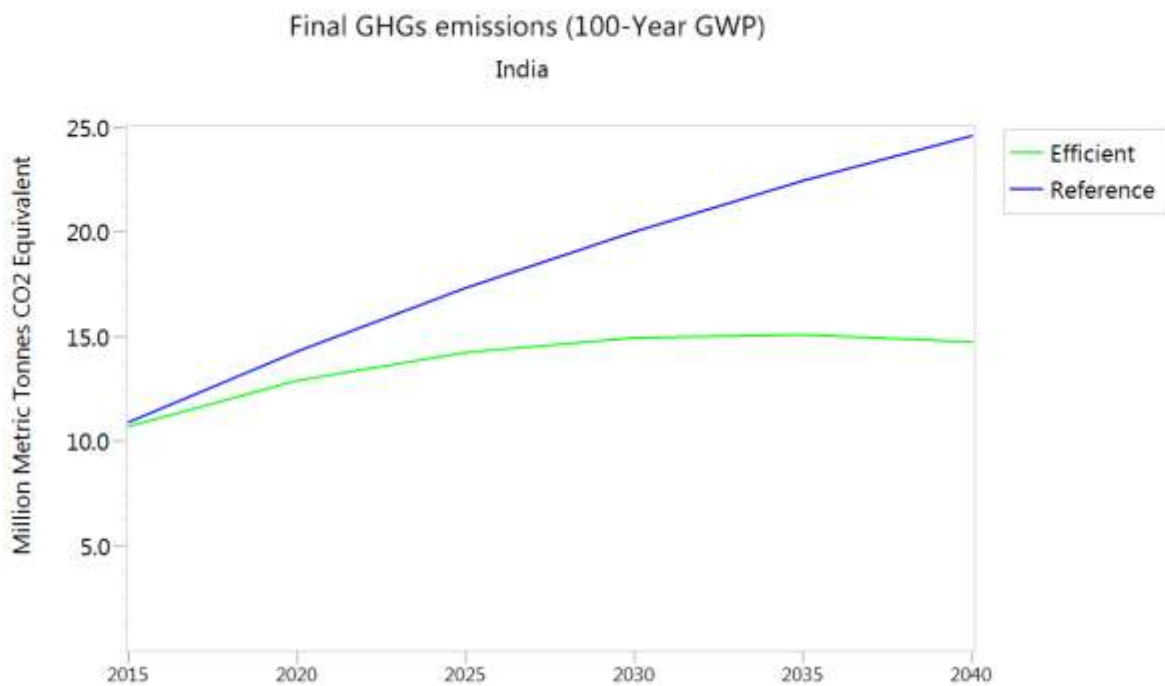

Figure 39: Final GHG emissions (CO_2 Equivalent) for India in the reference and efficient scenarios

As per Figure 39, slum household's GHG emissions in India grew from 10 million tonnes (103 kg per capita) in 2014 to 15 million tonnes (214 kg/capita) and 25 million tonnes (356 kg/capita) under the efficient scenario and reference scenarios respectively by 2040. India's slum population is expected to reduce from about 22 million households in 2014 to 16 million households in 2040. As reflected in the figure 39, although the number of slum population decreases still the final energy consumption increases due to the increase in the diffusion of end-use devices and unit energy consumption. Global emissions reported in human development report (UNDP 2007) for India is 1.2 tonne per capita but this level includes emissions airisng from areas other than residential emissions as well. However 356 kg/capita emissions in the reference scenario can be futher reduced to 214 kg/capita in 2040 if the efficient scenario is realized by slum households. Therefore it can be safely said that meeting the energy needs through efficient energy systems only contribute a very small proportion of global emissions. This result shows direct GHG emissions at the point where emissions are produced in 100 year GWP values. The emissions reflect the energy demand corresponding to where the emissions were produced.

Figures 40 & 41 present final GHG emissions (CO_2 Equivalent) for Kenya and Bangladesh in the reference and efficient scenarios. Both countries are expected to grow their slum population and energy consumption during the study horizon.

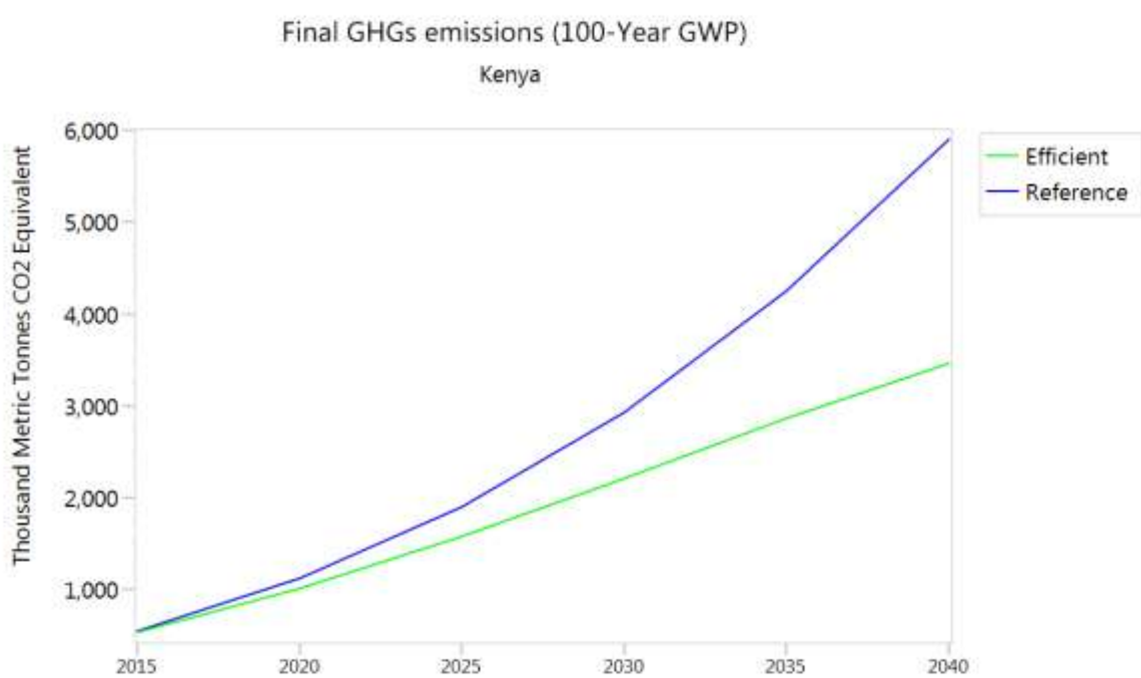

Figure 40: Final GHG emissions (CO_2 Equivalent) for Kenya in the reference and efficient scenarios

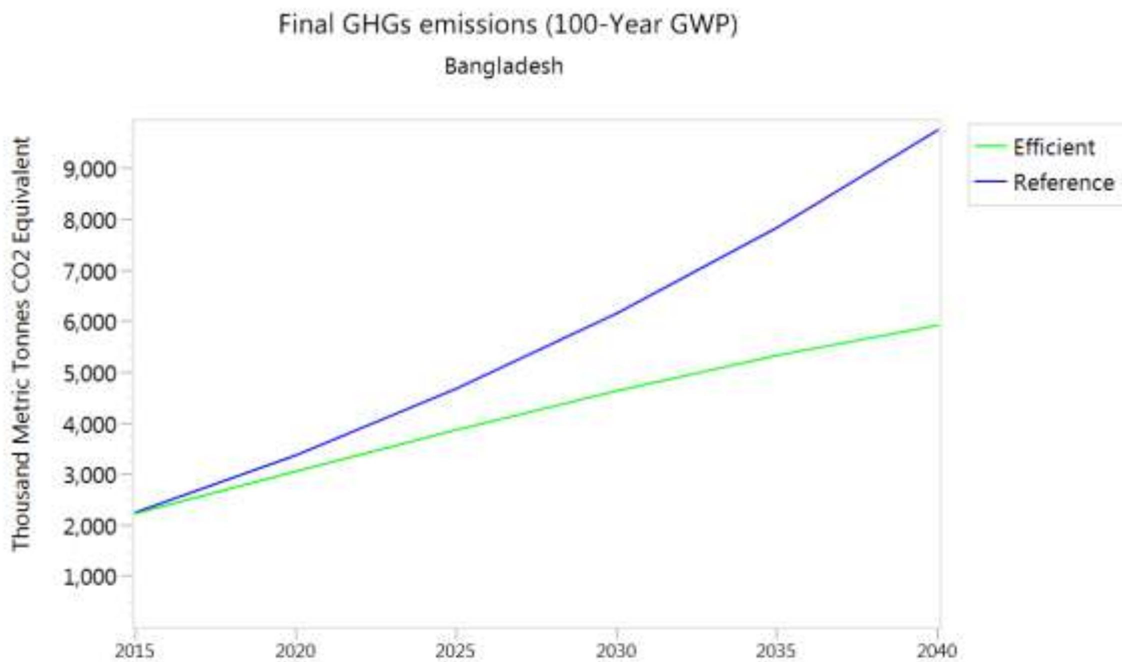

Figure 41: Final GHG emissions (CO_2 Equivalent) for Bangladesh in the reference and efficient scenarios

Slum household's GHG emissions in Kenya grew from 450 thousand tonnes in 2014 to 3500 thousand tonnes and 6000 thousand tonnes under the efficient scenario and reference scenarios respectively by 2040. Whereas, Bangladesh' slum household's GHG emissions grew from 2 million tonnes in 2014 to 6 million tonnes and 10 million tonnes under the efficient scenario and reference scenarios respectively by 2040. It is noteworthy that Kenya's slum population growth (5%) is much higher than Bangladesh's slum population growth (1.2%) in the study horizon. However Bangladesh' GHG emissions in 2040 is three and five times respectively in the efficient and reference scenario compared to its 2014. Whereas Kenya's GHG emissions in 2040 is eight and thirteen times respectively in the efficient and reference scenario compared to its 2014. In this regard, Kenya's GHG emissions intensity is growing faster than Bangladesh.

6.4 Overall emissions reduction potential

The biggest final emissions reduction is associated with the use of electricity fuel as energy sources via efficient lighting and appliances as presented in Figure 42. However, cooking end-use is responsible for a net increase in emissions due to the more penetration of LPG stoves nevertheless in a small amount of about 1.9 million tonnes in 2040. Total final net emissions reduction that is achieved by the efficient scenario is about 58 million tonnes in 2040.

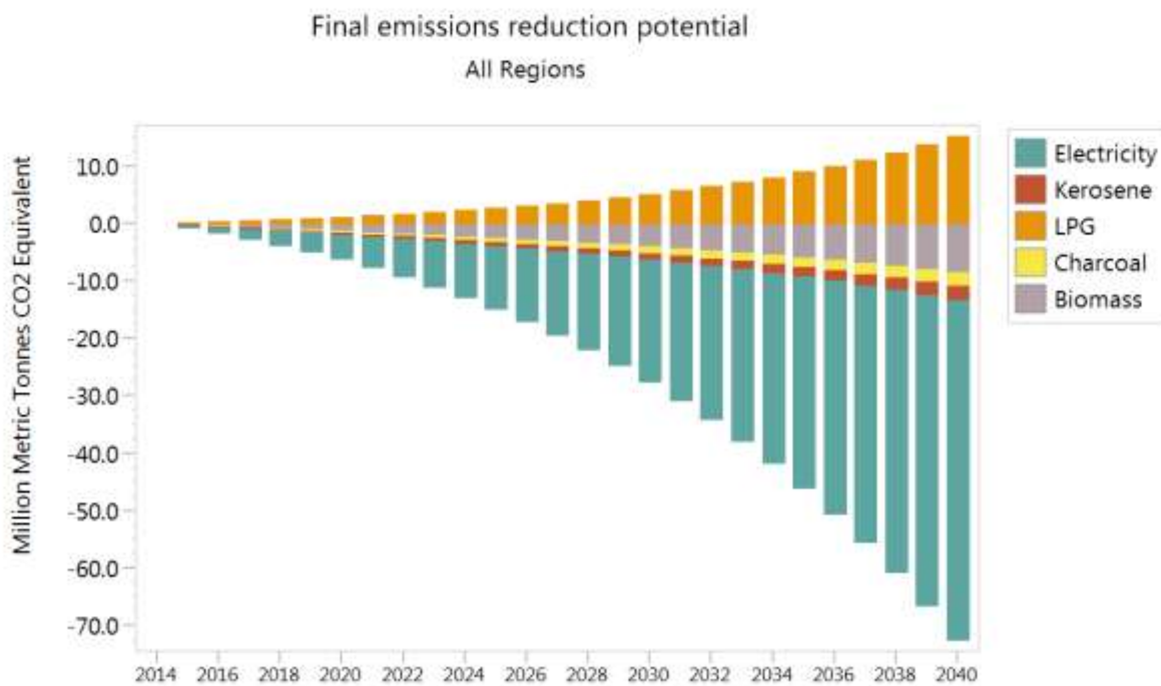

Figure 42: Final GHG emissions reduction potential by energy source, 2014-2040

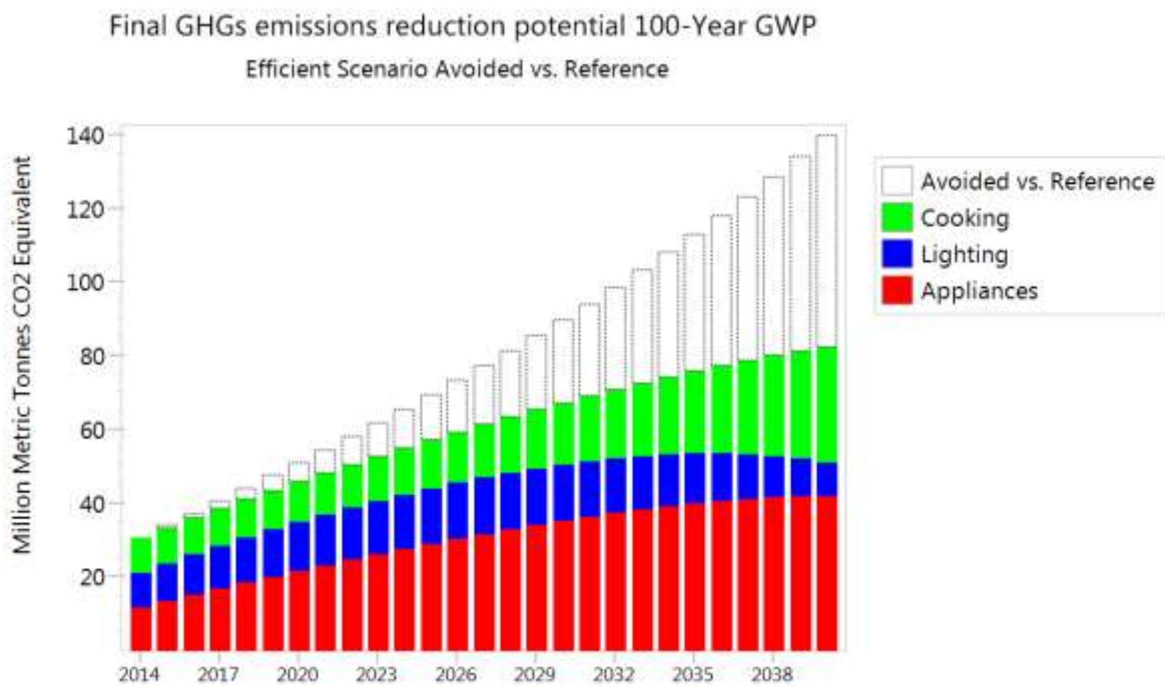

Figure 43: Final GHG emissions reduction potential (represented by Avoided vs. Reference) from realizing the efficient scenario in the selected years

GHG emissions reduction from all regions in 2040 by transitioning to energy uses to the efficient scenario is 58 million tonnes (Figure 43; Table 18). As stated earlier, cooking end-use causes a net increase in emissions due to the adoption of universal LPG connection. However, emissions are reduced from other cooking devices such as fuelwood, charcoal, and kerosene stoves because of their significantly low usage in the efficient scenario. LPG although being a fossil based fuel is a clean and efficient source of energy with the potential of rapid adoption if appropriate policy measures are taken.

Table 18: GHG emissions reduction in Million Metric Tonnes CO_2 Equivalent (in selected years)

End-uses	2015	2020	2025	2030	2035	2040
Cooking	-0.2	-0.9	-1.3	-1.2	-0.3	1.9
Lighting	-0.1	-0.9	-2.5	-4.8	-8.3	-14
Appliances	-0.3	-3.3	-8.4	-16.5	-28.4	-46
Total	**-0.6**	**-5.1**	**-12.2**	**-22.5**	**-37.0**	**-58.1**

The total cumulative GHG emissions reduction of 550 million tonnes CO_2 Equivalent can be realized between 2014-2040 by realizing the efficient scenario (Table 19).

Table 19: Total (cumulative) GHG emissions reduction in Million Metric Tonnes CO_2 Equivalent until 2040

End-uses	Until 2040
Cooking	-15
Lighting	-121
Appliances	-414
Total	**-550**

To put the emissions reduction figure into a context, as per the Emissions Gap 2016 report emissions consistent with the 1.5-degree scenario is 39 $GtCO_2e$ in 2030 (UNEP 2016). The report states that the emissions gap between emissions level achieved by Intended Nationally Determined Contributions (INDCs) and the emissions level consistent with the 1.5-degree scenario are 17 $GtCO_2e$ (UNEP 2016) in 2030. Looking from emissions reduction that is achieved by the efficient scenario, roughly a half Gigatonne CO_2e (550 MMT CO_2e) over the period between 2014-2040 is very small from global environmental perspectives. Therefore in order to justify the investments needed to provide efficient energy sources to urban poor, governments need to look beyond climate benefits and focus on the developmental benefits (co-benefits) that these efficient energy sources bring.

6.5 Conclusion

The GHG emissions analysis provides a good understanding of the importance of sustainable energy provision to slums from environmental and developmental perspectives, and the policy implications of energy efficiency measures from slums context. The analysis further supports the idea that mitigation and development should not be dealt in isolation. This analysis also helps in providing evidence-based energy efficient pathways in urban poor context.

The levels of GHG emissions under the efficient scenario and reference scenarios respectively in 2040 are: 82 million tonnes and 140 million tonnes. Household GHG emissions in the SA and SSA grew from 100 kg per capita in 2014 to 183 kg per capita and 311 kg per capita under the efficient scenario and reference scenarios respectively by 2040. A total reduction of 58 million tonnes GHG emissions are realized by the efficient scenario in 2040. Whereas, the total cumulative GHG emissions reduction of 550 million tonnes CO_2 equivalent can be realized during the study period by the efficient scenario. Further, results suggest that slum dwellers GHG emissions will still be far below the radar even in 2040 when compared with the current average regional and world emissions levels. Henceforth, meeting the slum households' energy needs through efficient energy systems only contributes a tiny proportion of the total world emissions but gains in human development are significant. Despite the decreasing trend of slum population in few countries such as India, an increase is registered in the final energy consumption mainly due to the increase in the diffusion of end-use devices and unit energy consumption.

Efficient lighting and appliances are the major sources of emissions reduction however cooking end-use causes a net increase in emissions of about 1.9 million tonnes in 2040. The reason behind this increase in cooking emissions is the universal penetration of LPG stoves. To remain below the 1.5-degree mean temperature, the Emissions Gap report (2016) states that despite the current best effort (via INDCs) the emissions gap of 17 $GtCO_2e$ will still remain effective. A roughly half a million tonnes CO_2e reduction that is achieved by the efficient scenario over the study period looks a meager contribution from the global environmental perspective. Hence a case is needed to be made from the developmental (co-benefits) perspective to realize the efficient scenario.

Furthermore, the results reveal that the countries experience a differing emission trajectories based on how their slum population, appliance diffusion, and unit energy consumption grow over the study period. For example, from the case of Kenya and Bangladesh it is shown that Kenya's GHG emissions intensity is growing faster than Bangladesh. Similarly the results can be used as comparative analysis of the countries emissions trajectories. However, it is outside of the scope of the dissertation to further analyze the reasons behind why individual countries experience different emissions trajectories.

Chapter 7: Discussion - Mitigation within a development context

The chapter describes the major findings from the analysis that environmental and developmental objectives go hand in hand by providing efficient energy end uses to urban poor. The chapter builds its argument from the research results that current energy uses from slum households are not significant compared to non-slum households. However in the context of rapid urbanization, economic growth and climate change the energy uses of slum households are expected to grow fast and may even reach the regional averages for many countries soon. Therefore, communicating why climate action associated with mitigation could have developmental advantages is crucial to gain traction for the effective climate change mitigation action. The chapter strengthens the viewpoint that doing so a future that is necessarily low carbon but that also fulfills human desires of a good life can be achieved. Further, in the chapter I look deeper into the key challenges and solutions for realizing the potential of the efficient scenario, discuss the policy relevancy of the research such as assessing the entry points at which policies will need to be introduced to be more successful.

7.1 Mitigation within a development context

In this section, environmental and other implications of the evolution of slum households overall energy system development keeping in view of the research results are discussed. The results of the scenario analysis suggest that the increase in energy consumption and GHG emissions as a result of realizing efficient scenario is relatively small from the global environmental perspectives. This is so regardless of the particular efficiency trajectory that may take hold decades into the future. Even if all slums transition to "regular" urban dwellers, this will only add a small percentage to energy use. Meanwhile, socio-economic co-benefits of improving access to efficient energy use in these settlements are significant. Achieving energy efficiency among slum households could also improve the physical environment and health, greater earning capacity, increased disposable income, and hence generate development co-benefits. Moreover, scenarios show that this can be achieved for much less energy and emissions in the efficient scenario. This is important because, at least from the perspective of slum households' energy use and associated emissions, the impact of slum upgrading - an enabler of efficiency scenario, would remain below the radar of even the most ambitious climate goals such as those promulgated in the Paris agreement.

The relationship between energy use and developmental benefits are more direct in the urban poor households. It is because they have to make decisions about fuels and appliances and at the same time experiencing many of the costs and benefits of such decisions themselves (Dasgupta et al, 2011). The link between energy consumption and developmental aspects among urban poor households, in fact, works both ways. For instance, inefficient energy usage along with fuel scarcity can aggravate the livelihood security of urban poor. Addressing energy problems alone cannot solve the developmental problems as there are other contributing factors that affect poverty among urban poor. Therefore measures to improve energy efficiency can provide developmental benefits related to its use but in order to help poverty, these will have to be a part of a larger and integrated program such as slum upgrading that addresses the causes of poverty among urban poor (Dasgupta et al, 2011).

While the complete benefits of greenhouse gas reductions resulting from energy efficiency actions may only be realized by future generations whereas the developmental benefits are immediate. For example, urban poor purchase fuel in smaller quantities due to resource limitation, they pay more per unit of energy consumed than their richer counterparts hence they spend a larger proportion of their limited income on energy (Dasgupta et al 2011). Therefore cost savings as a result of energy efficiency actions would provide direct and immediate benefits to the urban poor. There are high interests in investing in efficient cook stoves such as LPG in towns and smaller cities in the developing countries probably from the perspective of improved health than from potential energy savings.

In countries within the studied regions, improved stoves have been mainly promoted in rural areas because of easy availability of fuelwood. However due to less availability of fuelwood to the urban poor, stoves such as LPG immediately improve their lives. Urban poor households represent a nuclear family structure and are more educated than their rural counterparts. They are hence more open to adopting new ideas and practices. They have to spend money rather time on acquiring fuel. Therefore the time saved in fuel collection is reflected in cost savings compared to many rural areas where fuel is still considered as a free resource despite the labor and time involved in fuel collection. Urban poor are also more likely to spend money on buying the stove than constructing by their own especially if the cost of the stove is comparable with the stove type they currently use (Dasgupta et al, 2011). Hence, urban poor are perhaps more likely to be benefitted from efficient stoves as LPG stoves than the rural poor.

Energy is profoundly connected with social and economic development, and therefore the impact of energy efficiency actions go far beyond energy savings. Energy efficiency improvements can be the main contributor to the economic and social development along with environmental improvement. Due to this reason, the quest for energy savings should no longer be seen as an end in itself rather means to make practical improvements in various aspects of society (Ryan and Campbell 2012, Pearce 2000). At the same time energy efficiency is a key tool to achieve climate mitigation and therefore the deliverance of energy savings cannot be compromised but should be looked at their full potential. Policy makers should consider such tradeoffs between energy savings and socio-economic welfare gains and a balance should be struck in designing energy efficiency policies (Ryan and Campbell 2012; Pearce 2000; Tyler 2015). Some outcomes of energy efficiency actions may be indirect or there may be intermediate steps involved to establish causality (Ryan and Campbell 2012). Hence it is important to identify the multiple impacts of energy efficiency actions and to evaluate their overall and relative importance so that they are considered as part of the mainstream economic policy and their full socio-economic potential is delivered (Raubenheimer et al. 2015).

Benefits of energy efficiency are indeed numerous for human health, environment, job creation, productivity, high quality of services for people, lower dependence on fossil fuels, and for society at large. The research highlights that development goals and mitigation need do not need to be at odds. An integrated approach that tackles these joint concerns together can bring multiple co-benefits in slum households. If meaningfully integrated into decision-making processes, co-benefits arising from mitigation action present an opportunity for realising win-win synergies and cost-savings (ACP 2014).

7.2 Challenges for realizing the potential of the efficient scenario

To remain below the 1.5-degree mean temperature, the Emissions Gap report (2016) states that despite the current best effort (via INDCs) the emissions gap of 17 GtCO2e will still remain effective (UNEP 2016). A little over half Gigatonne CO_2e reduction that is achieved by the efficient scenario over the study period looks a meager contribution from the global environmental perspective. Countries as they are directed by international treaties (e.g. UNFCCC) to reduce their GHG may find the low potential as hindrance for action to provide efficient energy services to urban poor especially from the environmental perspectives. This is precise the reason that a strong case is needed to be made from the developmental (co-benefits) perspective to facilitate efficient energy services in the developing and low income countries especially for the fast growing slum households.

Governments may focus on the cheapest GHG emission reduction options which may not be the ones that offer the most development benefits for instance HFCs reduction from factories. It is not clear, however, whether the cheapest greenhouse gas emission reduction options which particularly are highlighted in the international carbon markets (Clean Development Mechanism; the voluntary markets) are also the ones that will bring the most developmental benefits. Many of these project funding bodies are mostly motivated by the net reduction in GHG irrespective of their larger societal benefits hence prioritize the projects that follow the least cost reductions (Rowlands 2011).

One cannot expect that an efficient energy technology such as used in the efficient scenario will be adopted and used by the urban poor the way its designer originally intended (Keirstead and

Shah 2013). The dominance of technological perspective alone is no longer perceived as true. Keirstead and Shah 2013 note that "users bring their own meanings to energy technology and use them within a complex web of social norms, personal values and decision making context". In this regard it is argued that the main drivers influencing adoption of the efficient energy technology depends on the level of household, on factors like income, education levels & compatibility with their use practices (Ruiz-Mercado et al. 2011). Although there is anecdotal evidence in favor of households positive response to fuel savings, cooking speed, convenience, and pollution issues of efficient technologies. Also two main challeges of high up-front cost and high fuel cost are a big hindrance in the uptake and sustained use of efficient appliances.

At the same time, another challenge is that irrespective of how important it is to find out the energy savings and emission reduction potential of slum households transition to the efficient energy system, policy making and implementation of research findings will not happen automatically. To establish this information basis to facilitate implementation, it is important that knowledge provided by research is 'translated' or 'brokered' for use by decision makers (as knowledge users). To facilitate this brokering role space has to be created for policy innovation by better coordinating the interface between policy research and policy or decision making. At the same time, scientific research such as this dissertation finding is only one of the many parameters that actually play a role in policy making sometimes important and sometimes not so important.

There are however inherent problems between science and policy integration. Scientists as knowledge producers and policy makers as knowledge users have different outlooks such as their aims, attitudes towards information, languages, perception of time, and career tracks differ (Choi et al 2005). Also if there are no interactions between scientists and policy makers, as a result scientists may not be aware of the financial and political reality, implementation of research results, such as this, most likely will not happen. The urgency that drives scientists and policy makers or knowledge users is different, along with how the knowledge is produced and what is considered to be good evidence. The relative accountabilities also differ between scientists and policy makers. However, scientific research such as this has an important, if modest, place in policy making.

As described above, with rapid urbanization poverty is shifting to urban areas in developing countries leading to slum formation. At the same time efforts for mitigating climate change are also becoming more urgent. However, in these countries, poverty alleviation efforts are mainly focused on rural areas and mitigation strategies rarely recognize that a vast majority lives in poverty. To add a further complication to this situation, policy makers perceive climate mitigation and poverty alleviation as conflicting public policy objectives. Also, most mitigation actions can have positive or negative impacts on poverty based on the way they are designed and implemented.

There is a need to address both mitigation and adaptation to the increasingly damaging effects of climate changes. Successful mitigation acitivities in these rapidly developing cities is key to achieving worldwide stabilization in the emissions of GHG. These areas are also home to large populations of urban poor who are most vulnerable to the effects of global change. When local environmental problems are addressed together with global environmental problems, slum settlements living in these cities can 'tunnel through' the curves which is famously associated between increase in wealth with the increase in environmental quality in the developed countries. Doing this has the potential to tackle the challenge of rapid growth, emission mitigation, and increasing resilience to climatic shocks in urban poor (Oliveira, Doll, and Suwa 2013).

7.3 Overcoming the challenges: potential entry points to break the hurdle

It is clear that to support an increasing number of urban poor with increasing level of wealth while respecting critical planetary boundaries, efforts to diffuse and scale energy efficiency technology must be accelerated. Energy efficiency is one of the most effective and economically advantageous means to combat climate change. Energy efficient devices provide environmental and socioeconomic development benefits and optimize those benefits by extending run times and leaving more electricity for other uses to highly cost sensitive urban poor population. Therefore achieving energy efficiency among slum households could improve the physical environment and health, greater earning capacity and hence increased disposable income (Dasgupta et al, 2011). Below I highlight few entry points that could potentially facilitate the implementation of the efficient scenario results.

One aspect of the solution is to identify synergies between mitigation and development actions as stressed throughout the chapter. For example, a focus on the reduction of Short-Lived Climate Pollutants (SLCPs) from the introduction of LPGs instead of existing dominant use of fuelwood, charcoal and kerosene stoves as cooking device would not only benefit residents health and wellbeing but also potentially reduce emissions. Short-lived climate pollutants are gases and particles that contribute to warming and have a short lifetime (few days to 10 years). SLCPs include black carbon (BC), tropospheric ozone (O_3) and its precursors CO, nmVOC and NOx, methane (CH_4), and some hydrofluorocarbons (HFCs) those are emitted during the incomplete combustion of biomass based fuels mainly used by the urban poor. Policies that highlight SLCPs reduction may become an entry point to achieve both climate mitigation and development objectives. Also, due to SLCPs short lifetime the climate benefits are received earlier than the other GHG with long lifetime.

Pine et al., 2011, working with improved Patsari cookstoves in Mexico identified community of residence, number of adults in household, suffering from irritated eyes, using wood scraps for fuel, and cooking with certain types of traditional fogons as factors influencing early adoption. Based on their study on dissemination of improved patsari cookstove in Mexico, they recommend using NGO networks for effective dissemination and measuring success on the basis of stove use over time rather than on the total number of stoves disseminated. They also found that product-specific characteristics (usage cost, device price, safety etc.) need due consideration to develop appropriate design with high probability of acceptance as they are easily modifiable in short time periods (Takama et al. 2012).

Pachauri et al. (2012) suggests that a reorientation of subsidy policies from fuel to end use devices to tackle the challenge of upfront cost is required in order to increase the diffusion of efficient devices among poor households in the developing world. Since slum households have high internal discount rates, innovative financing that can convert upfront cost into a payment stream over a longer period of time is an effective strategy to help them adopt efficient appliances. Energy efficiency can further improve access. For instance slum households have suppressed energy needs and when with the help of saved energy costs they are even able to increase their energy services to meet all the basic needs. Another policy which is appliance standard is useful in increasing the bar for availability of efficient appliances in the market (Koeppel et al. 2007). Slum households do get benefits from the progressively improving appliance standard and labeling policies but may be with some time delay as generally they do not buy the new appliances (Pachauri etc al. 2012). Therefore subsidies for fuels together with appliance standards, labeling, and financing schemes to meet the challenge of high upfront cost would steer slum households towards making an informed choice to help realize the efficient scenario. For better and comprehensive impact it is recommended to integrate these forward looking policies into slum upgrading programs/activities.

In order to reduce the upfront cost of LPG, smaller cylinders are introduced in Kenya (6kg), India (5kg), and Thailand (3kg) with associated gas burner and poor are allowed to buy gas in smaller as per their income levels starting from one kilogram (Singh 2015). Also, in Kenya a program called "Stima Loan" (an electricity loan) allows new customers pay only 20% of the upfront connection fee. They allow the balance to be paid over 2-3 years in monthly installments at an annual interest rate of 15%. Such schemes enable more slum households to access electricity (Nyabundi D 2012). In Kenya, government also subsidizes the electricity cost where users consume less than 50kWh of electricity which are billed at a lower rate and termed as – 'lifeline tariff'. Programs such as these enable slum households to overcome the energy challenge and use more of efficient energy sources (Singh 2015). At the same time, to avoid the misuse energy subsidies has to be used smartly. Tripathi el al (2015) suggest that LPG subsidies targeted to urban poor be termed as social investment at par with other public investments such as primary healthcare and schools as the national health and social benefits could be huge.

The main challenges for the diffusion and adoption of the efficient and modern appliances among the slum households are the high up-front cost and credit constraint which affect their energy related decisions. Subsidies although eases the high fuel cost, alone they are ineffective as they are unable to affect high up-front cost. Improved financing opportunities helps in meeting high up-front cost of efficient appliances. When subsidies (fuel price support) are combined with improved financing (such as micro-financing for credit access) together they are most effective in meeting the challenges of high up-front and fuel cost (Pachauri et al 2012).

Provision of efficient household fuel such as LPG to the world's poor would be miniscule to the environmental burden of fossil fuels. According to Smith (2002) even if all the world's poor start using LPG as cooking fuel, it would only contribute to less than 2% to the global GHG emissions. However, a shift to LPG would be immense in terms of improving the health by net reduction of air pollution which is greater compared to total exposure from all fossil fuel emissions.

GNESD study (2008) found that slum households are unaware of the negative health and environmental risks associated with the biomass use while having fears and doubts about the safety of LPG. Due to this reason there is need for the outreach and awareness programs to dispel these safety myths of the use of efficient sources of energy while highlighting the adverse impact of biomass use. The study suggests that integrated urban energy centers that could serve as one stop shops for providing information, selling efficient appliances, and fuels so that slum households can receive immediate access of information and energy sources. As per the study, this could become a good basis for action.

Singh et al (2014) found that to address these energy challenges will require actions at multiple levels in policy innovation by recognizing the needs of urban poor, promoting institutional coordination, removing the barriers of tenure, relaxing the formal requirements of electricity connections, identifying synergies between slum upgrading and energy policies, introducing easy payment methods, and nurturing social inclusion and co-operation.

There are several new innovative models of energy provision and development which are currently being considered such as based on renewable energy generation on household level, sharing economy, circular economy etc. Implementation of these innovative development models would further increase the savings potential and further reduce emissions. Examples include when a household generates energy from solar PV or when several households share a refrigerator on communal basis coupled with efficient appliances a further savings and emission reduction can be achieved on top of what is possible with efficient scenario alone as analyzed in this study. The analysis of such models of development and their respective savings and emission reduction potential should be considered as extension of this research and indicates future research direction.

7.4 Policy relevancy of the research

To achieve the energy savings and emission reductions that have come out from the results of this analysis, the efficient scenario, that can be considered as one feature of sustainable urban development paths and must be considered. Energy savings and emission reduction from energy efficiency measures are considered as one of the three dimensions for achieving such sustainable urban development path along with resilience and quality of life. At the same time, it can be argued that energy efficiency measure also increases resiliency and quality of life (Pickett et al. 2013; UN 2015). However, the current urban development policies and paths in the studied countries do not align with achieving the required sustainability. Urban areas are increasingly perceived as center-point for driving environmental change at numerous scales (Grimm et al. 2008). Achieving the three dimensions, resource efficiency, resiliency and quality of life would require financial, societal, and political actions and innovations. In fact these are not the competing objectives rather should be addressed in combination to create synergies which will further enable to gain political capital to make them fulfilled in the multi-contested arena of urban politics (Kabisch and Kuhlicke 2014).

Co-benefits of climate mitigation policies are realized in terms of reduction in local pollution control in the near-term. Therefore co-benefits may act as windows of opportunities or entry points for such ambitious climate change mitigation policies in the studied countries by compensating some share of GHG mitigation costs in the short-term (Bollen et al., 2009). However in the medium run the only benefit of climate mitigation policies are the co-benefits or developmental benefits since the direct benefits of such policies will occur in the longer-term only.

Mitigation actions that offer synergies with short-term development goals are important in the context of urban poor households in the low income and developing countries. Mitigation option that involves providing energy efficient appliances to urban poor offer immediate and local economic and welfare benefits (Fay et al. 2015). At the same time, this will help ensure that climate considerations are well integrated into countries developmental objectives. For instance, some analyses reveal that health benefits as a result of climate mitigation policies alone would outweigh mitigation costs in many developing countries until 2030 (Shindell et al. 2012). By designing policies that focus short-term, local, developmental impacts could be the key to alter the relative attractiveness of various mitigation options which is also in strategic interests to poor people including slums living in the developing and low income countries (Rowlands 2011).

The case in point here is the framework of Poverty Alleviating Mitigation Actions (PAMA) proposed by the Mitigation Action Plans and Scenarios (MAPS) program which provides a conceptual and practical tool to effectively combine both the objectives of climate mitigation and poverty alleviation (Wlokas et al 2012). In order to reduce both emissions and poverty, PAMA framework suggests that – i) poverty alleviation goals need to be clear, time-bound and quantifiable, ii) examining actions based on feasibility and potential impacts of developmental goals on mitigation and poverty, and iii) the actions to achieve such goals need to be selected from these findings. The PAMA framework can help to highlight the public policy on urban poverty and mitigation. The framework can also help to identify and inform the synergies and tradeoffs in selecting mitigation actions in urban poor context. Using the framework, a conventional mitigation action can be turned into a PAMA with the right mix of policies and incentives. Therefore using such PAMA framework actions for urban poverty alleviation and climate mitigation can be effectively combined.

Similarly, much has been written on advancing climate mitigation policy in developing countries. However, whilst most authors make the point that development priorities are critical, and some attempt to a coherent approach to development, this has largely been from the perspective of whether climate mitigation and development objectives can be achieved simultaneously. Far less attention has been paid to what development means for how domestic policy is made and implemented and from there what the implications of this are for the increasingly urgent task of advancing climate mitigation policy in developing countries. Another viewpoint is that climate mitigation can be conceptualized as co-benefits at both a conceptual and practical level, suggesting that a co-benefits approach can elevate development aspects in the climate mitigation discourse (Tyler 2015). Successful implementation of climate change policies is even more important for the urban poor in the developing and low income countries, as their cities are in earlier stages of development and can avoid many of the problems faced in the past in the developed countries.

A policy approach based on co-benefits or developmental benefits would have potential to integrate climate concerns into local development, which naturally considers the local situation (Oliveira, Doll, and Suwa 2013). Social and environmental benefits include reduced mortality by providing efficient cook stoves such as LPG or costs such as indoor air pollution caused by traditional cook stoves. A whole suite of tools available to estimate welfare changes which are often based on estimates of willingness to pay (WTP) for benefits or willingness to accept for compensation of losses (Perman et al., 2003). Although such social benefits and costs are important to estimate, they deem a complete research on their own rights. However social and developmental benefits accrued by implementing efficient scenarios signals avoided costs, for example, the amount of expenses saved on not providing subsidies on kerosene or the electric grid which do not need to be built.

In order for improved energy efficiency efforts to have developmental impacts, policies must be designed to target the needs of urban poor. The evaluation of energy efficiency programs in the past focused mostly on technical efficiency and rapid and mass diffusion rates which are not the appropriate indicators to measure the developmental impacts (Dasgupta et al, 2011).

7.5 Conclusion

At the one end where developed countries are faced with the challenge of transforming their high carbon energy systems to low carbon systems, low income and developing countries challenge is to increase energy supply to support much needed economic development in a most carbon neutral and economically efficient means possible (Forum For the Future 2016). As long as slum households are concerned which are mostly located in these low income and developing countries, reducing GHG emissions do not appeal them very much and seems abstract to them. The urban regions in the developing world should instead focus on co-benefits such as air pollution, noise pollution, health benefits, and cost savings as the other tangible measures of sustainability for the increased buy-ins and effective strategic actions that ultimately reduces GHG emissions as well. A transformation is needed in energy systems to mitigate climate change. Climate change is a global problem while implementation is local. Therefore we need to look ‘mitigation within development context’ in these countries. There is a need for the development and mitigation communities to come together and work collaboratively to make this transformation happen.

Challenges to realize the efficient scenario can be met by smart designing of policies targeted to solve the current and future energy challenges of urban poor. Social innovation shaped by new adaptive business models have the potential to create breakthroughs where governments do not reach and make profits on the way. Improving the urban fabric by upgrading slums will extend the benefits of a compact, energy-efficient built environment to slum dwellers and provide a more inclusive improvement in quality-of-life for all urban residents. Upgrading slums supported by the energy policy can bring multiple benefits to slum dwellers for a relatively small energy premium in building operation. Development should be climate compatible because although slums are neither the cause of the climate situation nor the rescuer but they are the one most vulnerable to any climate shocks.

Chapter 8. Conclusion

In the dissertation, I have estimated final energy demand savings and GHG emissions reduction potential of slums transition to efficient energy technologies until 2040 in 52 out of 57 countries in South Asia and Sub-Saharan Africa. The research goal throughout the dissertation is to find out how large are the total energy savings and GHG emissions reduction potential of slums transition to efficient energy systems. The dissertation results help in understanding the importance of sustainable energy provision to slums from environmental and developmental perspectives, and the policy implications of energy efficiency measures from slums context.

The framework of bottom-up, end-use accounting technique is applied using scenario modeling approach to make projections about the whole slum population. It includes detailed technological information for end-uses. Long range Energy Alternatives Planning System (LEAP) model developed by SEI is used to forecast activity level, final demand, energy savings, and GHG emission associated with the realization of efficient scenario. The two scenarios that are used in the research are reference and efficient scenarios. In the reference scenario, slum households meet the basic level of energy services fully in 2040. However, the energy demands are met by inefficient appliances. Whereas in the efficient scenario, basic needs of energy are fully met and sustainably in 2040, using efficient appliances.

I found the energy savings from sub-Saharan Africa and South Asia in 2040 by transitioning of energy uses to efficient scenario is 474 billion kWh. Results suggest that overall about 67% energy savings can be achieved in 2040 from all end-uses and energy sources compared to the reference scenario. Cumulatively 46% energy savings (5260 Billion Kilowatt-Hours) can be achieved in the study period (2014-2040) from the efficient scenario while all basic energy needs are fully met. The levels of GHG emissions under the efficient scenario and reference scenarios respectively in 2040 are: 82 million tonnes and 140 million tonnes. Household GHG emissions grew from 100 kg per capita in 2014 to 183 kg/capita and 311 kg/capita under the efficient scenario and reference scenarios respectively by 2040. A total reduction of 58 million tonnes GHG emissions are realized by the efficient scenario in 2040. Whereas, the total cumulative GHG emissions reduction of 550 million tonnes CO_2e can be realized during the study period by the efficient scenario. When compared to the reference scenario, energy savings and emission reduction potential are significant. Even though 550 million tonnes or roughly half a gigaton GHG emission reduction achieved in the study period may seem small from the global environmental perspective, the dissertation has shown that the developmental benefits or co-benefits as a result of these energy efficiency actions are critical for the achievement of the Sustainable Development Goals (SDGs).

About 87% of total energy savings come from fuel switching that takes place in the cooking end use whereas about 10% and 3% energy savings arise from appliances and lighting end uses in 2040. Energy savings by achieving the efficient scenario from individual end-uses compared to reference scenario in 2040 are - cooking: 70% (415 billion kWh), lighting: 59% (13 billion kWh), and appliances: 52% (46 billion kWh). However, energy consumption from LPG increases by about 50% (58 billion kWh) while consumption from biomass is reduced by 87% (464 billion kWh) in the efficient scenario compared to reference scenario in 2040.

The results suggest that building efficiency criteria at the very beginning of providing energy access, effective energy supply is reduced significantly, and the level and quality of energy services is improved. This provides a way for increasing number of urban poor to develop without increasing emissions i.e. ‘mitigation within a development context’ – a low carbon future that also fulfills human desires of a good life. This is important because climate change is a global problem however the implementation of the climate mitigation takes place at the local level. Therefore communicating the role of developmental benefits that the mitigation action brings are important in terms of gaining traction for the effective climate change mitigation action. In essence, the research connects the dots between the Paris Agreement, Sustainable Development Goals (SDGs), and New Urban Agenda, in order to build a sustainable urban roadmap that brings the global slum community towards a better future.

Although the shift to urbanization and increasing economic wealth are great, the emission reduction potential (in the efficient scenario compared to reference scenario) is not commensurate when contrasted with the kind of extensive reduction we need to remain below 2 degree Celsius. However there are huge co-benefits involved from mitigation actions such as switching to more efficient end uses to slum households. Development should be climate compatible because although urban poor are neither the cause of the climate situation nor the savior but they are the one most vulnerable to any climate shocks. Therefore we need to look ‘mitigation within development context’ in these countries. Due to this reason there is a need for the development and mitigation communities to come together and work collaboratively.

Energy efficient appliances offer a variety of sustainable development benefits to slum household families. For example use of LPG stoves, although uses fossil fuel resources, reduces deforestation and indoor air pollution that further improve respiratory health, and free up time that would have been spent collecting wood for women to childcare or work and increased school attendance of children. High up-front cost and high fuel cost together with lack of awareness about the efficient energy systems are a big hindrance in the uptake and sustained use of efficient appliances. Therefore in order to help realize the efficient scenario it is recommended that subsidies for fuels together with progressively increasing appliance standards, labeling, and financing schemes (to meet the challenge of high upfront cost) would steer slum households towards making an informed efficient choice. Reduction of Short-Lived Climate Pollutants (SLCPs) from efficient LPG cooking is a good way to identify synergies between mitigation and development actions. At the same time product specific characteristics need due consideration such as making the availability of smaller LPG cylinders to increase the affordability by urban poor. The need of the hour is to integrate these forward looking policies into slum upgrading programs/activities for better and comprehensive impact. The Paris Agreement places such climate action at the center of making progress towards achieving sustainable development. The agreement recognizes climate mitigation co-benefits as precursors to foster sustainable development. However in order to achieve the ambitious plan set by the agreement limits temperature increase to 1.5-2C above pre-industrial level, concerted efforts from governments, civil sector, and significant funding from the private sector are essential.

The Paris Agreement and the 2030 SDGs agenda go hand in hand and are co-dependent which means one can't succeed if the other fails. Therefore for a transition to a sustainable and equitable world, efforts must be transformational and delivered at a fast pace. SDGs act as instrument to achieve sustainable development hence are lever to secure a win-win situation that supports a more prosperous future for all the inhabitants of the world. The dissertation results highlight the mitigation options from slum households that are consistent with their countries own goals and priorities, and not dictated by the international profit seeking mechanisms such as project funding bodies acting upon the international carbon markets motives to explore least cost mitigation options which may not provide larger societal benefits. Further the dissertation emphasizes the importance of three major areas of action: contributions by non-state actors, energy efficiency acceleration, and synergies with the achievement of the SDGs.

This analysis also helps in providing evidence-based energy efficient pathways in urban poor context. The research results can be used as comparative analysis of the countries' energy consumption and emissions trajectories. However, it is outside of the scope of the dissertation to further analyze the reasons behind why countries experience different energy consumption and emission trajectories. This could be a future research using the dissertation results as starting point to further analyze the reasons behind the differing trajectories of different countries in the study region. Further, the dissertation research could be used to complement the regional study with a country or city level study to get a more detailed treatment of the topic. Further, the impact of new and innovative models of energy provision and development such as based on renewables, circular and sharing economy can be researched which can build more efficiency on top of what is achieved in the efficient scenario elaborated in this dissertation.

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