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Research Project

Low-cost energy technologies for Universal Access

A Comprehensive Computer-Aided Planning Approach for Universal Energy Access

Case Study of Kilifi, Kenya

Lily MWALENGA¹, Reja AMATYA¹, Andres GONZALEZ-GARCIA², Robert STONER¹,
Ignacio PEREZ-ARRIAGA^{1,2}

¹ Massachusetts Institute of Technology, USA

² IIT Comillas University, Spain

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Research Project Low-cost energy technologies for Universal Access

The UN Secretary General's Advisory Group on Energy and Climate Change defines Universal Access as "access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses". The International Energy Agency (IEA) establishes that achieving a minimum basic Universal Access to electricity and providing clean cooking facilities for 2030 would require around \$1 trillion cumulative investment. IEA also highlights electricity as the most critical energy carrier for development while the use of biomass in inefficient stoves remains one of the main causes of premature deaths.

It is clear that a problem of this magnitude cannot be seriously approached without private capital and, most likely, with the serious involvement of energy companies, although decentralized approaches – either transitory or not – cannot be ruled out and they are already taking place. Obviously this will happen only if an attractive business model can be defined. This model must include: the definition of the appropriate (low cost) technologies to be used; a regulatory framework that clearly defines the rights and obligations of all parties involved and, specifically, the rules of remuneration for the provision of the service; and the sources of finance for this activity. Such considerations are central to this research project and represent a considerable challenge for rural areas.

The purpose of this project is to contribute to the development of Universal Access strategies and tools for policymakers, global businesses and practitioners, supporting the publication of periodic technologies, strategies and business models country reports with roadmaps to universal access.

This Working Paper 5 refers to the case study in Kenya, developed in the Phase II of the *Low cost energy technologies for Universal Access* project by the Massachusetts Institute of Technology (MIT) acting through MIT's Energy Initiative (MITe) and in collaboration with Fondazione Centro Studi Enel (Enel Foundation). The project is developed in collaboration with Comillas Pontifical University – Institute for Research in Technology (COMILLAS – IIT) under the scope of the Comillas University Massachusetts Institute of Technology Electricity Systems (COMITES) Program.

Phase I of the project comprises the State of the Art technologies, strategies and business models for electrification (Working Paper 1) and modern heat (Working Paper 2) as well as the proposal of a methodology to develop country studies for the establishment of roadmaps to universal access (Working Paper 3).

Final working papers 4 and 5 discuss the results for the model as applied to two countries: Peru and Kenya. We have applied our methodology to the regions within these countries to develop a comprehensive assessment of the appropriate modes of electrification and cooking for the entire population. We have investigated business practices that have been adopted around the world for the dissemination of these technologies. We have also focused on the existing regulatory, governance and financing frameworks that enable the sustainability, replicability, scalability and upgradability of these technologies and business models in order to provide long-term, reliable and affordable access to modern energy services for all.

This publication includes the results of the models for Universal Access to Modern Heat and Electricity for Kilifi County in Kenya.

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Abstract

In 2009, it was estimated that 1.4 billion people in the world lack access to electricity, and approximately 2.7 billion people rely on biomass as their primary cooking fuel. Access to reliable electricity and modern forms of energy for cooking can contribute to improvements in sectors beyond the energy industry such as health, education, commerce, and agriculture, and has been shown to correspond with poverty alleviation and economic growth. A successful strategy towards universal access requires a careful assessment of the diverse energy services needs from the perspective of the beneficiaries, the impact on their economic and social development, and the environmental consequences. This Working Paper proposes a comprehensive methodology for the assessment of the appropriate modes of electrification and heating and cooking for specific countries or regions. The software tools used for this analysis are incorporated in the proposed technology toolkit consisting of: the Reference Electrification Model (REM)—used to determine the appropriate modes of electrification (grid extension, micro or isolated systems) given the current base scenario; and the Reference Cooking Model (RCM)—used to determine technology choices for the provision of modern heat for cooking. While the analytical strategy presented here is intended to be generalizable for other regions, it is based on a case study of Kilifi County in Kenya. The larger goal of this project, through the case study approach, is to provide a proof of concept for the decision support tools being developed that could be used in energy access expansion planning.

Keywords: *Universal Access, off-grid electrification, grid extension, modern cooking technologies, business models, energy policy, regulation*

Jel Codes: Q4, Q41, Q42, Q43, Q47, Q48, N70, O13, O18, O19, O33, O38, O44, Q56

Corresponding Author

Reja Amatya
Massachusetts Institute of Technology,
77 Massachusetts Avenue, Building E19-432
Cambridge, MA, 02139-4307
Email: ramatya@mit.edu

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1. Introduction and situation analysis

1.1 Framing of Universal Access planning and policy-making

The UN Secretary General's Advisory Group on Energy and Climate Change (SG AGECC, 2010) defines Universal Access as “access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses”. Access to modern energy services is a key element for human development and is central for achieving the Millennium Development Goals (IEA, 2010; UN Energy, 2005; World Bank, 2013).

The International Energy Agency (IEA) highlights electricity as the most critical energy carrier for development. In 2012, it was estimated that 1.3 billion people in the world lack access to electricity, a number expected to drop by 2030, but only to 1.2 billion. The majority of these people are in sub-Saharan Africa, where it is projected that the proportion of the un-electrified population will increase in 2030 primarily because the rate of population growth will exceed the rate at which access to electricity is being provided. Approximately 90% of the population without modern energy services already spend so much on batteries and traditional options (kerosene lanterns, candles) that they could afford to purchase better alternatives (such as solar lamps) (IFC World Bank, 2012), although only for the most basic services of lighting and phone charging.

The question of what it means for a household in developing countries to have electricity access has a complex answer. The way in which access is defined has important implications for planning and design consideration. The IEA defines initial electricity access at two levels of consumption: 250kWh for rural households and 500kWh for urban households per year. The SE4All Global Tracking Framework has 5 tiers that range from 1W peak available capacity for four hours a day—task lighting and phone charging—to over 2,000 W peak available capacity for over 22 hours a day—medium and high-power appliances (IEA & World Bank, 2014). While both approaches are technology neutral (encompassing both grid and off-grid solutions), the latter is interesting in that it measures both access to electricity supply and the use of electricity services.

Though growing interest in energy access issues in developing countries has led to more open discussions and more funding opportunities, much of it is focused on electrification needs. The statistics on access to clean cooking and heating fuels in the developing world, however, are just as (if not more) staggering as the electrification challenge, and ensuring access to modern fuels demands at least as much urgency.

About 2.7 billion people, projected to rise to 2.8 billion by 2030, rely on biomass (fuel wood, charcoal, agricultural waste, and animal dung) as their primary cooking fuel (see **Figure 1-1**) (IEA, 2010). Although the proportion of households using solid fuels has declined, the actual number of people without access to clean fuels has remained largely constant primarily due to population growth. As Bonjour et al. (2013) show, there is a close relationship between traditional cooking solutions and poverty, demonstrated in the strong correlation between biomass usage and low per capita GDP.

Number of people relying on the traditional use of biomass for cooking	
Africa	657
Sub-Saharan Africa	653
Developing Asia	1 937
China	423
India	855
Other Asia	659
Latin America	85
Developing countries*	2 679
World**	2 679

*Includes Middle East countries. **Includes OECD and transition economies.

Figure 1-1: Number of people (*in millions*) relying on biomass for cooking, 2009 (IEA, 2010)

These fuel sources emit dangerous levels of greenhouse gases and hazardous particulate matter, and pose elevated risks for uncontrolled fires. The World Health Organization estimates that illnesses resulting from household air pollution caused by the inefficient use of solid fuels are responsible for 4.3 million premature deaths annually (WHO, 2014). As of 2010, indoor air pollution caused more premature deaths than tuberculosis or malaria (a comparison is shown in **Figure 1-2**).

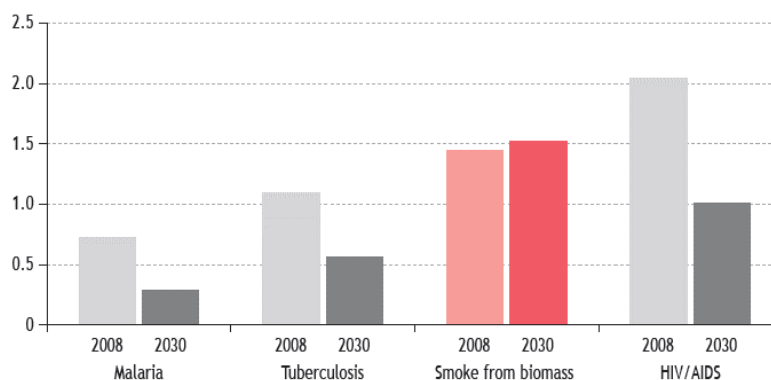


Figure 1-2: Premature annual deaths from household air pollution and other diseases (*millions of people*) (IEA, 2010)

Health hazards are not the only issues that arise from the use of traditional fuels. Collecting wood, dung, and other types of biomass requires a significant amount of time and sometimes also money. While the fuel itself is free as people are able to collect it themselves to cook and heat their houses, the time it takes to gather these fuels could be spent on more productive or health-protecting activities. In addition, the use of traditional biomass stoves increases pressures on local natural resources and contributes to climate change at the regional and global level.

A significant gender component also exists: women (and children) take on the greatest share of the health burden associated with the use of traditional fuels because they spend the most time at home (GEA, 2012). They also typically bear both the physical burden and the time burden of collecting, transporting, and processing the fuels. Women and girls can spend upwards of 20 hours each week collecting fuel for their families (WHO, 2006), and may face increased security risks during their search.

Access to reliable electricity and modern forms of energy for cooking can contribute to improvements in sectors beyond the energy industry such as health, education, commerce, and agriculture, and has been shown to correspond with poverty alleviation and economic growth (Lipscomb et al., 2013; Khandker et al., 2012; GEA, 2012; Dinkelman, 2007; Wolde-Rufael, 2009; Yoo, 2006). An illustration of this is seen in the correlation between the Energy Development Index¹ (EDI) and the Human Development Index² (HDI), as shown in **Figure 1-3** below.

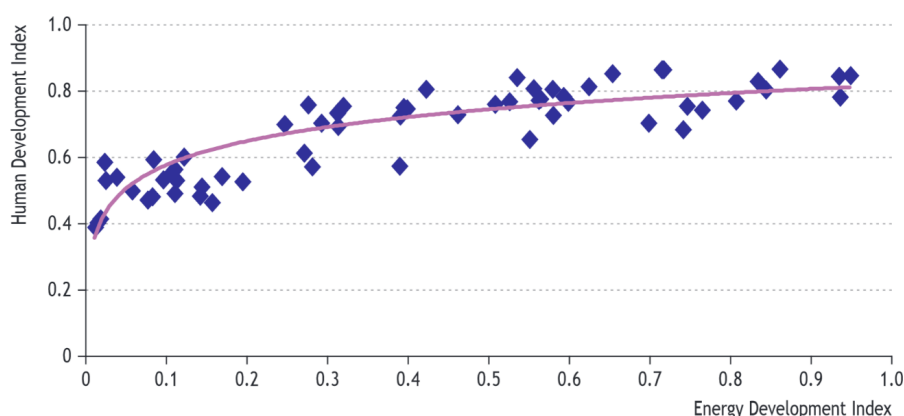


Figure 1-3: The relationship between the HDI and the EDI (IEA, 2010)

According to the IEA, “[a] new financial, institutional and technological framework is required, as is capacity building in order to dramatically scale up access to modern energy services at the local and regional levels” (IEA, 2010). It is from this viewpoint that this research has been conducted.

1.2 Aim

The larger goal of this project, through the case study approach, is to provide a proof of concept for the decision support tools being developed that could be used in energy access expansion planning. In the end, the results can contribute to a general planning scheme that incorporates appropriate technologies, effective business models, compelling regulatory proposals, and sound institutional governance in order to contribute to the creation of an enabling framework for achieving universal energy access.

1.3 Methodology

A successful strategy towards universal access requires a careful assessment of the diverse energy services needs from the perspective of the beneficiaries, the impact on their economic and social development, and the environmental consequences. The software tools used for this analysis are incorporated in the proposed technology toolkit consisting of:

- The Reference Electrification Model (REM), used to determine appropriate and least cost modes of electrification (grid extension, micro or isolated systems),

¹ The EDI is an indicator based on per capita commercial energy consumption, per capita electricity consumption in the residential sector, share of modern fuels in total residential sector use, and share of population with access to electricity.

² The HDI is a composite index based on life expectancy, education and per capita Gross National Income.

- The Reference Cooking Model (RCM), used to determine technology choices for the provision of modern heat for cooking

The complete suite of models for decision making can be used to develop electrification and modern fuels plans for a region under specified constraints, subsidies & priorities; evaluate the impacts of these plans on the overall energy system, and answer what if policy questions such as:

- What are the implications, in terms of cost and supply technologies, of different assumptions regarding the energy demand to be met (to cover just the minimum basic needs, to allow some growth, and be compatible with productive and/or community uses)?
- What environmental effect will providing access to modern energy services have? On:
 - Indoor air pollution and the associated health impact
 - Deforestation
 - Climate change

While the analytical strategy presented here is intended to be generalizable for other regions, it is based on a case study of Kilifi County in Kenya. Kilifi was selected for the following reasons (Njonjo, 2013):

- Its low electrification rate (16.7% compared to 23% nationally) and the high proportion of households using tin lamps as their primary source of lighting (62.6% compared to 38% nationally).
- A greater percentage of households (68%) rely on primitive fuels—primarily wood—compared to the national average of 64%, although more households (28%) use transition fuels—primarily charcoal and kerosene—than the rest of the country (17%).
- The high estimates of people living below the poverty line (58% compared to 45.2% nationally), despite the county’s potential to be a major economic hub.

1.4 Energy Policy Planning

There is a wealth of commentary on policy planning for energy access and energy infrastructure development in emerging economies more broadly (e.g. Foell, 1985; de Oliveira & Girod, 1990; Abdulla & Markandya, 2012; Coelho & Goldemberg, 2013; Pueyo et al, 2014). Chapter 23 of the Global Energy Assessment provides a useful summary of some of the challenges to be addressed by a policy for access to modern energy services (GEA, 2012). The key principles from this discussion are provided below (GEA, 2012):

- The need for good understanding of the energy services to be addressed, along with reliable analysis.
- The recognition that energy activities are not just another industry, but a system with strong socioeconomic and environmental dimensions, with direct impacts on the sustainable development of any country.
- Long-term commitments from governments, with explicit and clear public policies oriented toward poor people.
- The need for soft funds and financing mechanism to develop infrastructure and to provide up-front costs for the potential consumers.

- Direct government involvement in implementation, through public utilities, private or non-profit organizations, or adequate public-private cooperation.
- Oriented subsidies (direct or indirect) to create enabling economic conditions.
- The conditioning of access to modern forms of energy for poor people clean appliances in addition to clean energy forms.

In terms of cooking and heating needs, five key issues have been identified as important in cooking energy planning (Ashden India & Shakti Foundation, 2015):

- i. The need to integrate multiple objectives in technology choice and product design.
- ii. Delivery mechanisms and market development.
- iii. End-user affordability and the bridging of financing gaps.
- iv. Fuel management for processed biomass.
- v. Renewed policy stance that is supportive but cognizant of user needs.

2. Kenya

Bordered by Somalia and the Indian Ocean to the east, Ethiopia and South Sudan to the north, Uganda to the west, and Tanzania to the south, Kenya covers a surface area of 582,646 km² and is divided roughly in half by the equator (KNBS, 2014b). The country is divided into 47 counties, each with their own regional government, for administrative purposes. Nairobi, the capital, serves as a major commercial hub in the East African region.

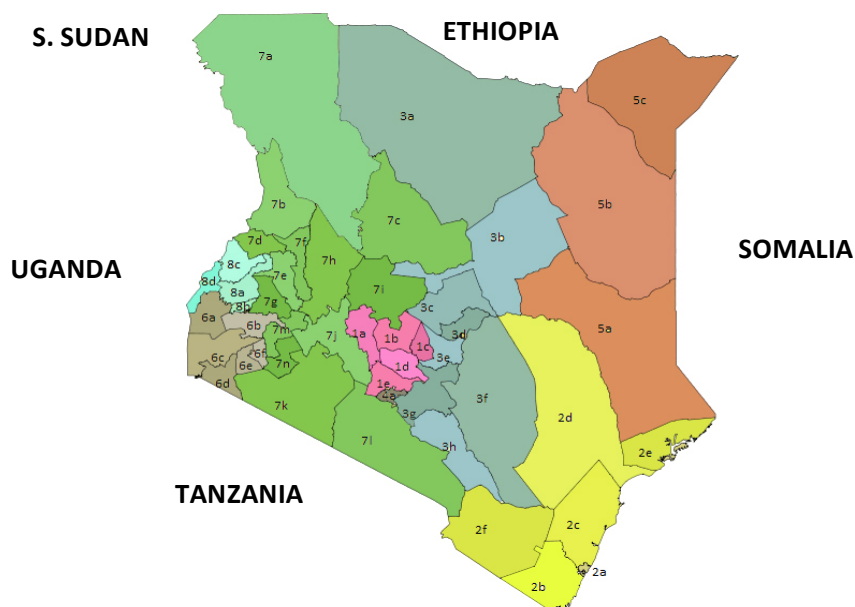


Figure 2-1: Administrative map of Kenya (co2balance & GACC, 2013)

Kenya's terrain varies from low coastal plains in the east to the central highlands, which are bisected by the Great Rift Valley, a fertile region with vast geothermal resources (SWERA, 2008). There are 5 main drainage basins, with the Tana River in the east having a series of hydroelectric dams that provide almost two thirds of the country's electricity.

According to the Kenya Population and Housing Census of 2009, the country had a population of 38,610,097 in 8,767,954 households (KNBS, 2014c), a number that as of 2015 was estimated to have increased to 45.9 million (CIA, 2015). Approximately 74.4% of the population is rural, and the most densely populated areas are in the central and southwestern parts of the nation (CIA, 2015).

Approximately 45% of the population lives below the poverty line³, majority of which are located in the northern and eastern parts of the country. This number is higher in rural areas (51%) than in urban areas (33%). The poverty gap⁴ (as a percentage of the poverty line) is

³ The poverty line, obtained by estimated consumer expenditure, is a threshold below which people are deemed poor. In the 2005/06 KIHBS, the poverty line was estimated at KES 1,562 and KES 2,913 per adult equivalent per month for rural and urban households respectively.

⁴ The poverty gap is an estimate of how much on average would be needed to bring each household from their current income to the poverty line.

12%, but ranges from 46% in Tana River County to 4.1% in Nairobi, highlighting huge disparities also observed in the national Gini coefficient⁵ of 0.445. (Njonjo, 2013)

Kenya serves as a regional hub in Eastern and Central Africa for finance, trade, and communications. Though integrated with several global value chains (in floriculture, textiles, leather, manufacturing, and tourism), there have been minimal social and economic benefits (Odero & Reeves, 2013). Kenya's annual percentage growth rate of GDP at constant prices has averaged 5% over the past 5 years and is projected to increase to 6% in 2015 (World Bank, 2015b; KNBS, 2014b). The per capita GDP on a purchasing power parity basis in 2014 was estimated at USD 3,100 (in 2013 USD) (CIA, 2015).

In order to address some of the development challenges Kenya is facing, the government proposed a long-term national planning strategy, Vision 2030, with the aim of transforming the country into an industrialized, middle-income country. The plan is built on a dedication to macroeconomic stability, science and innovation, major infrastructural investment, human resources development, and public sector reform (RoK, 2007).

2.1 Electrification

Kenya's electricity sector has traditionally been dependent on hydropower (44% of effective capacity), with an estimated potential of 3-6 GW, of which 1.5 GW of the undeveloped potential is thought to be of economic significance (RoK, 2011b). Current hydro installation stands at just under 820 MW (KPLC, 2014). Although there is increasing awareness of possibilities of small hydro, only a few small hydro schemes (in the range of 0.5-1.5 MW) have been realized. Geothermal is the next big resource available in Kenya's Rift Valley system, with an estimated prospect of 5-10 GW potential (RoK 2011b). The country currently has 363 MW of installed geothermal capacity. Kenya receives a considerable amount of solar radiation throughout the year, making it an ideal location for solar installations. As of 2011, there were an estimated 200,000 PV solar home systems (rated between 10-20 We) currently in use in the country. More than 6 MW of solar PV capacity was installed in both the residential and commercial sector as of 2014. The coal used in Kenya is primarily imported from South Africa and Asia, and its use is limited to industries for heating furnaces and steam generation.

Results from the 2009 census showed 22.9% of the population listed electricity as their main source of fuel for lighting. **Figure 2-2** shows this breakdown, along with the primary sources of lighting for those unelectrified, where tin lamps and lanterns take up almost 70% of the market. **Table 2-1** shows the percentage of households with various appliances in the country.

⁵ The Gini coefficient, a measure of the distribution of income across a population, varies between '0' reflecting complete equality and '1' indicating complete inequality.

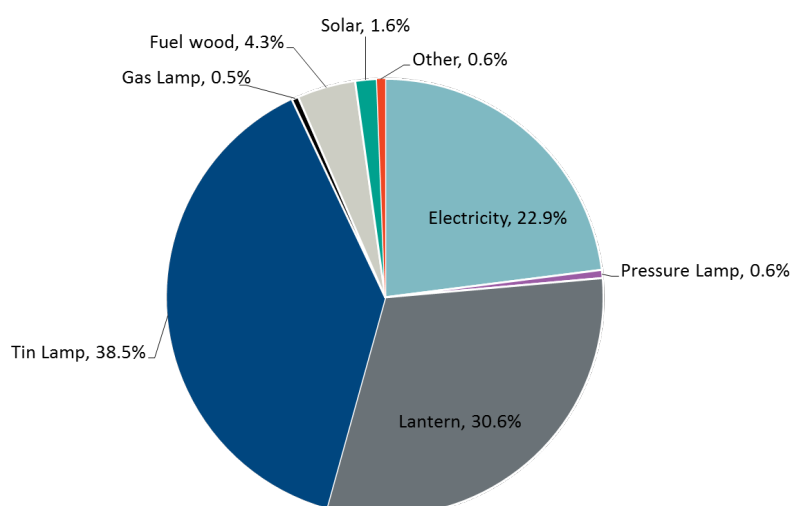


Figure 2-2: Primary source of lighting by household, 2009 (KNBS & SID, 2013)

Table 2-1: Household appliance ownership, 2009 (Minnesota Population Center, 2014)

Appliance	Households (%)
Landline Phone	1.4
Mobile Phone	65.9
Radio	70.3
TV	30.6
Refrigerator	5.8
Computer	4.1
Automobile	6.0

The Rural Electrification Program (REP) has also seen rapid expansion with consumption almost two-fold more in 2013/14 than in 2008/09, with total customers connected under the scheme at 528,522 as of June 2014 (RoK, 2015a). **Table 2-2** shows the electricity sale across the country from 2008-2014.

Table 2-2: KPLC sales for REP schemes (GWh) (KPLC, 2014)

Region	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14
Nairobi	52.0	55.3	62.6	63.0	66.0	109.0
Coast	16.0	18.3	20.9	21.2	22.0	24.0
West	125.0	134.8	153.1	151.9	152.0	216.0
Mt. Kenya	57.1	70.5	70.4	71.9	73.0	105.0
TOTAL	250.1	278.9	307.0	308.0	313.0	454.0
% Increase p.a.	2.7%	11.5%	10.1%	0.3%	1.6%	45.0%

As of June 2013, about 66% of the country's public facilities had been electrified (**Table 2-3**). The Rural Electrification Authority also financed the installation of isolated diesel generators in 13 towns in off-grid areas primarily in the north and northeast, with 2 located along the coast (REA, 2013).

Table 2-3: Electrification status of public facilities (REA, 2013)

Facility	Electrified	Unelectrified	Total
Trading Centers	9,174	2,868	12,042
Secondary Schools	7,879	335	8,214
Health Centers	3,905	768	4,673
Primary Schools	10,157	11,065	21,222
Water Projects/Boreholes	1,967	1,784	3,751
<i>Total</i>	<i>33,082</i>	<i>15,820</i>	<i>49,902</i>
<i>% Electrification</i>	<i>66%</i>	<i>34%</i>	<i>100%</i>

According to Brinckerhoff: Kenya Distribution Master Plan, the connection cost for a new customer for a single phase power line is KES 34,980 (~USD 383) and KES 49,080 (~USD 537) for a three-phase connection within a 600m radius to a sub-station. As of early 2014, Kenya Power was looking to increase the connection charge to about KES 75,000 (~USD 821). There is however, talk of switching to a different system (single wire earth return) to bring down costs and maintain rates at KES 35,000.

Grid performance and reliability (as well as price) can have a large impact on consumer decisions when choosing a system for electrification. An analysis using grounded theory and system dynamics to model feedback in the development of the electric power system in Kenya can be found in Steel (2008). The off-grid market exists as an alternative for residential customers to low availability, high costs of connecting to the grid, and long response times. This also makes it competitive for industrial customers to generate their own power (Steel, 2008), as can be seen in **Table 2-4** where more than half of surveyed enterprises own or share a generator.

Table 2-4: Quality of electricity infrastructure (Pueyo 2015, with data from the 2013 World Bank Enterprise Survey)

	Kenya	SSA	All Countries
Number of electrical outages in a typical month	6.3	7.8	5.6
Duration of a typical electrical outage (hours)	4.9	5.0	2.7
Losses due to electrical outages (% of annual sales)	5.6	4.9	2.5
Percent of firms owning or sharing a generator	56.8	45.7	32.1
Proportion of electricity from a generator (%)	7.8	12.6	7.0
If a generator is used, average proportion of electricity from a generator (%)	14.2	24.6	18.8
Days to obtain an electrical connection (upon application)	42.4	32.8	31.1
Percent of firms identifying electricity as a major constraint	22.9	44.8	33.5

2.2 Cooking and Heating

Figure 2-3 shows the various energy sources and supply technologies for the provision of cooking energy use.

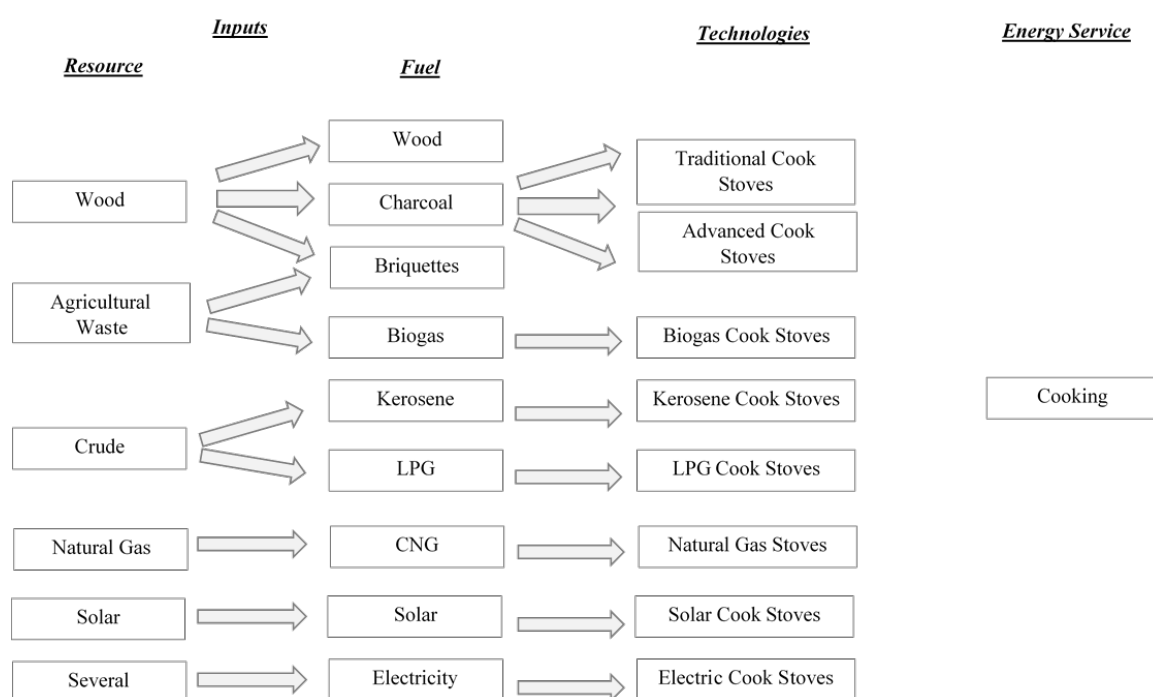


Figure 2-3: Choices of various energy sources and supply technologies for cooking

The main focus for universal access (particularly for rural communities) in cooking has been on the development, marketing, and dissemination of clean advanced cook stoves. The use of clean cook stoves and fuels can dramatically reduce fuel consumption and exposure to smoke during food preparation. International, national, and regional organizations have worked on various design solutions over the past number of decades, with the more innovative aspect of these efforts coming in the form of institutional models for selling the stoves, rather than actual stove design. In addition to more efficient stoves, the adoption of modern fuels such as LPG is equally important for achieving energy access in cooking.

The breakdown of the primary cooking fuel used in households per the 2009 census is shown in **Figure 2-4**. A greater percentage of households (65%) use primitive fuels—wood, animal and agricultural waste—with 29% use transition fuels—primarily charcoal and kerosene—and the remaining 6% use advanced fuels (KNBS & SID, 2013). Energy consumption patterns indicate households commonly use multiple fuels as opposed to simply substituting fuels as income rises, with fuel stacking occurring in 54% of households (co2balance & GACC, 2013; Dalberg, 2013).

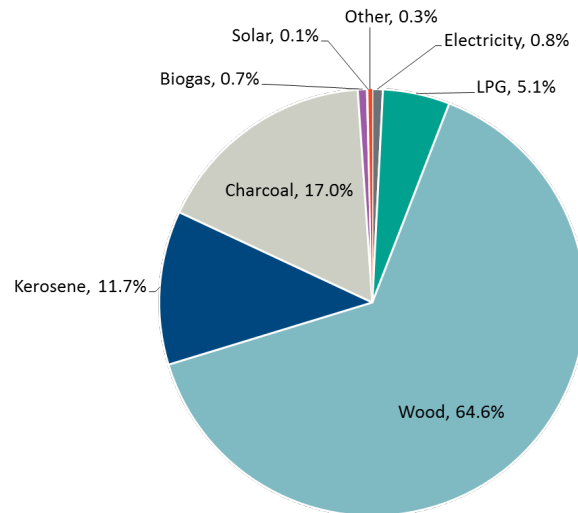


Figure 2-4: Primary source of cooking fuel by household (KNBS & SID, 2013)

The large majority (more than two-thirds) of households using wood and charcoal necessitate a discussion on the availability of wood. The FAO 2010 Global Forest Resources Assessment put Kenya's total forest area at just under 3.5 million ha (approximately 6% of land cover), declining at around 0.3% every year. Only 6% (208,020 ha) of forested land is designated for production purposes (FAO, 2010). **Figure 2-5** below shows the density of the country's woody biomass, followed by the results of a spatial analysis using a GIS platform to show wood fuel supply and demand patterns done by the FAO that highlights parts of central and western Kenya with high wood fuel deficits.

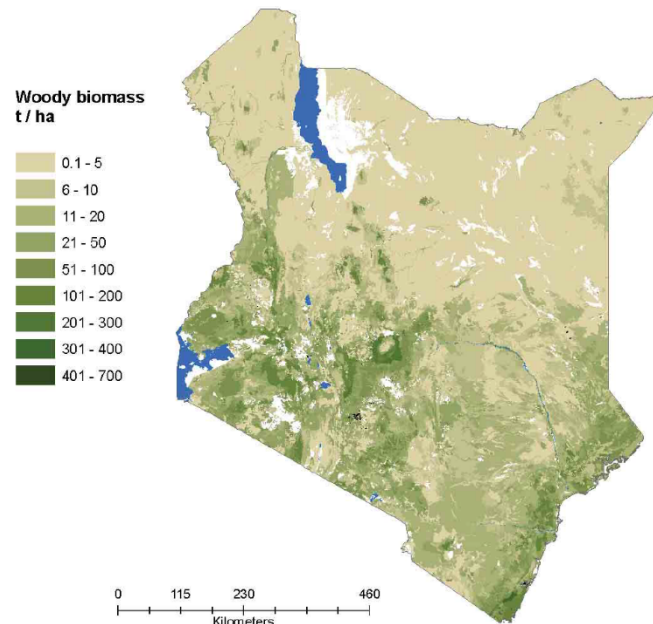


Figure 2-5a: Kenya woody biomass density map (Drigo, 2005)

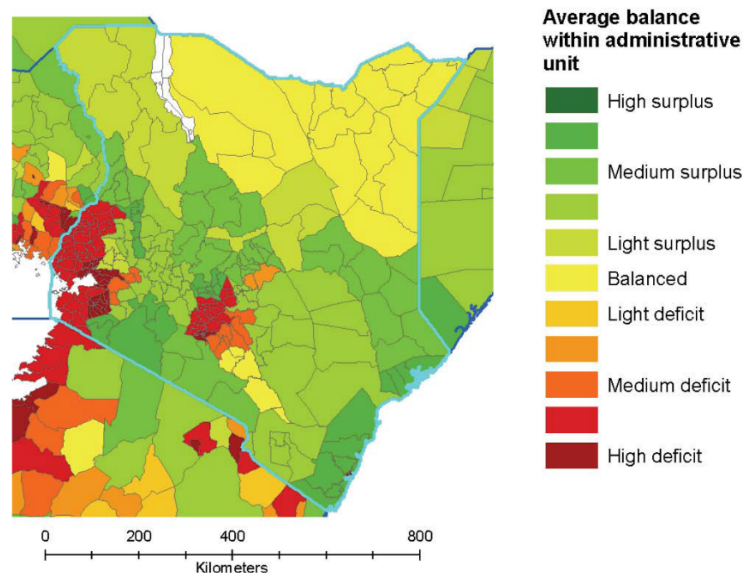


Figure 2-5b: Kenya average wood fuel supply-consumption balance by district boundaries (Drigo, 2005)

Wood for charcoal is sourced both legally and illegally, for an estimated annual production of 2.5 million tonnes in 2013, used primarily in urban areas (RoK, 2013b, co2balance & GACC, 2013). The use of briquettes, a fuel made by compacting biomass waste, is still a rather small fraction of overall energy consumption. Much of the briquetting taking place in Kenya uses charcoal dust, but expanding operations and diversification to other feedstock such as sugarcane bagasse could see briquettes displace as much as 5-10% of charcoal use (GVEP, 2010).

A biogas user survey conducted by SNV in 6 counties concluded that enormous potential for biogas technology existed. However, the high construction costs made it unaffordable, and more end user training was required to improve management once systems were set up (SNV, 2014). The Kenya National Domestic Biogas Programme (KENDBIP) was a five year implemented from 2009 to 2013 to facilitate the distribution and construction of 8,000 biogas digesters in order to improve the livelihoods of rural farmers and develop a commercially viable biogas sector (SNV, 2014; KENDBIP, 2011).

Kerosene is a cost-effective alternative fuel for the urban poor since it has enjoyed targeted subsidies (in the form of lower excise duty), although the ERC, PIEA, and the Kenya Revenue Authority have been pushing to raise these taxes in order to encourage consumers to use LPG (Agina, 2014; Senelwa, 2014). Despite high upfront costs and fuel costs, it is estimated that LPG penetration rates will reach 8-12% by 2020 (Dalberg, 2013).

The most prevalent cook stove technologies, as outlined by a GVEP Kenya market assessment report (GVEP, 2012), are shown below (**Figure 2-6**). The technologies have been assessed in WP2.



(a) Three-stone fire (wood)



(b) Upesi liner (wood)



(c) Kuni Mbili Stove (wood)



(d) Brick Rocket Stove (wood)



(e) Jiko Poa (wood)



(f) Envirofit G-3300 (wood)



(g) Traditional Metal Charcoal Stove



(h) KCJ (charcoal)



(i) Kerosene Stove



(j) Biogas Stove



(k) Classic Box Solar Cooker



(l) LPG stove



(m) Electric Stove

Figure 2-6: Cook stove technologies

2.3 Enabling Environment

Energy has been identified as a key enabler in achieving both the Millennium Development Goals and Vision 2030. Achieving financial measures that are harmonized with national energy policy and also considered within the larger framework of international commitments and initiatives (González-García et al., 2014). As such, energy sector reform is high on the government agenda in order to “facilitate [the] provision of clean, sustainable, affordable, reliable, and secure energy services for national development while protecting the environment” (ERC). The following sections describe current energy policy, regulation, and governance, as well as relevant key players in the national and international stage.

2.3.1 Energy Policy and Regulatory Framework

The *Constitution of Kenya 2010* created two levels of government, whose duties are set forth in Chapter 11 – “Devolved Government” and in the Fourth Schedule – “Distribution of Functions between the National Government and the County Governments”. The national government is responsible for national energy policy, public investment, and the protection of natural resources and the environment. County governments, under the directive of national policies, are responsible for regional planning and development including, among other things, electricity and gas reticulation, local energy regulation, and control of air pollution (RoK, 2010; TA & EISA, 2013; RoK, 2015a).

Policy and Legislation:

With the recognition of energy as a critical input to attaining the country’s economic development goals, *Sessional Paper No. 4 on Energy 2004* articulated the policy framework to sustainably supply adequate, quality energy services at least cost to consumers over 2004 – 2023. It set the stage for, among other things (RoK, 2004):

- The enactment of an Energy Act to promote regulation (through the establishment of a single independent energy regulator) and enhance stakeholder interests
- The establishment of a state-owned Geothermal Development Company (GDC)
- The creation of a Rural Electrification Agency (REA)
- The divestiture of government interests in oil refining and marketing, and in the Kenya Pipeline Company (KPC)
- The design of incentive packages to promote private investment in renewable energy and off-grid generation

The *Energy Act No. 12 of 2006* succeeded both the *Electric Power Act No. 11 of 1997* and the *Petroleum Act, Cap 116* in an attempt to collate Kenya’s energy law. It established and defined the powers and functions of the Energy Regulatory Commission (ERC), the Rural Electrification Agency (REA), and the Energy Tribunal. The Act also cemented the licensing for those engaged in the generation, importation or exportation, transmission or distribution of electrical energy or in the business of importation, refining, exportation, wholesale, retail, storage or transportation of petroleum (RoK, 2006).

Other principal policy and legislation includes:

- a. The *Geothermal Resources Act No. 12 of 1982*, to vest the country's geothermal resources in the Government and regulate their exploitation. (RoK, 2012b)
- b. The *Petroleum Development Fund Act, 1991*, which imposed a levy on all petroleum fuels consumed in Kenya to be paid into the Petroleum Development Fund established for investment in facilities for the distribution or testing of oil products and the expansion of the oil industry. (RoK, 2012c)
- c. The *2014 National Forest Policy*, which will put the implementation of community forest conservation and management, and thus the regulation of the charcoal industry, under county governments once effective (RoK, 2014a; Nation Correspondent, 2015b).

There are several proposed legislation currently being drafted:

- a. The *National Energy and Petroleum Policy 2015*, to address changes that could be expected in the sector with the unveiling of Kenya Vision 2030, the promulgation of the *Constitution of Kenya 2010* which transformed the country's governance structure, and the discovery of possibly commercially viable petroleum and natural gas deposits. (RoK, 2015a)
- b. The *Energy Bill, 2015*, to supersede the *Energy Act of 2006* once enacted and consolidates the country's energy laws and policies. The Bill as it currently stands establishes various energy entities (the Energy Regulatory Authority, the Energy and Petroleum Tribunal, the Rural Electrification and Renewable Energy Corporation, the Energy Efficiency and Conservation Agency, and the Nuclear Energy Institute) and covers licensing for the electricity and petroleum sectors as well as for coal exploration and development. (RoK, 2015b)
- c. The *Petroleum (Exploration, Development, and Production) Bill, 2015*, to provide a framework for the contracting, exploration, development and production of petroleum and the cessation of upstream petroleum operations. (RoK, 2015c)

Apart from the mentioned policies, there are specific regulations that deal with grid code, electrical installation, dispute resolution, electrical licensing, feed-in-tariffs, energy management, solar water heating, quota allocation for petroleum products, petroleum pricing, improved biomass cookstove, and charcoal regulation.

2.3.2 Funding and Financing

Funding for energy access in Kenya has been largely public, and it is generally directed towards large-scale infrastructure. Several multilateral institutions and funds continue to provide financing for such projects in Kenya, some key examples of which are listed below:

I. The World Bank

- The Kenya Electricity Modernization Project, to improve access through grant financing of new household connections, improve service delivery and reliability, and strengthen KPLC's financial viability
- The Kenya Private Sector Power Generation Support Project, to increase the proportion of IPP generation in the country

- The Kenya Petroleum Assistance Project, to strengthen the GoK's capacity to manage its petroleum sector and the revenue and investment streams for sustainable development

II. *Africa Development Bank*

- The Ethiopia-Kenya Power Interconnection, a 1,068 km high voltage direct current (HVDC) electricity highway with a power transfer capacity of up to 2,000 MW
- The Nairobi-Mombasa Transmission Line Project, to reinforce the transmission network and reduce losses
- The Power Transmission Improvement Project, expected to add about 580 km of 132 kV lines in order to extend power to rural areas
- The Menengai Geothermal Development Project, to generate up to 400 MW of power of an estimated potential of 1,650 MW
- The Lake Turkana Wind Energy Project⁶, which includes building 365 turbines expected to add 300 MW to Kenya's generating capacity (co-financed by the *East African Development Bank*)
- The Scaling-Up Energy Access Project, expected to benefit an estimated 25,500 households in Northern and Western Kenya, as well as several schools, health centers, and administration offices

III. *Climate Investment Funds*

The Scaling Up Renewable Energy Program in Low Income Countries (SREP), through demonstrations of the economic, social, and environmental viability of development pathways, aims to accelerate the deployment of renewable energy solutions and expand renewable markets in developing countries. SREP funding of USD 50 million has been proposed for use in a 200 MW geothermal development in the Menengai geothermal field, hybrid mini-grids, and the replacement of electrical water heaters with solar water heating systems. (RoK, 2011a)

Decentralized solutions, however, are typically more suitable for low-income households and those in more isolated areas. The lack of access is increasingly being seen as a market opportunity to deliver better alternatives. Approximately 90% of the population without modern energy services already spend so much on batteries and traditional options (kerosene lanterns, candles) that they could afford to purchase better alternatives (such as solar lamps), and an even greater fraction could afford ICS because of the gains in fuel cost savings (IFC World Bank, 2010). The rapid uptake of mobile phones in developing countries has demonstrated the potential for the diffusion of decentralized services through the use of innovative business models such as pre-paid platforms allowing the purchase of airtime in small bundles (Glemarec, 2012).

The challenge presents itself in high upfront costs for energy services technologies, which can be a large fraction of a low-income household's budget, and the fact that there is little

⁶ The Lake Turkana Wind Project suffered a setback in 2012 when the World Bank withdrew its support because they believed the power purchase agreement signed between the project and KPLC would "seriously compromise" the financial viability of the distribution company (Sambu & Wahome, 2012).

financing for end-use initiatives (Glemarec, 2012; Gubja et al, 2012). Poor households rarely get loans from proper lending institutions; an analysis of an eighteen-country data set showed that less than 5% and 10% of the rural and urban poor, respectively, had a loan from a bank (Banerjee & Duflo, 2011). People are forced to turn to informal moneylenders, where annual interest rates commonly vary anywhere from 40-200%, partly because of a high potential for default which requires a lot of effort (in time and money) on the part of the lender to enforce credit contracts and ensure the money is paid back (Banerjee & Duflo, 2011).

Microfinance institutions (MFIs) are thought to be well placed to be able to provide financing by adapting to the cash flow profiles of low-income households (UNCDF & UNDP, 2012). **Figure 2-7** below show some funding sources for end-users and small and medium enterprises in Kenya.

	MEMBERSHIP BASE	FUNDING METHODOLOGY	REGULATION
Formal institution			
Savings and credit co-operative societies (SACCOs)	Mutual membership organizations, such as SACCOs and ROSCOs. In 2005, there were 2,700 SACCOs with over 2.5 million members.	Pools voluntary savings from members in form of shares. Shares form basis for extending credit to members.	Regulated by the Co-Operative Societies Act (2007)
Kenya Post Office Savings Bank Ltd.	Individuals with small savings	Provides deposit services	Supervised and regulated by the Ministry of Finance
Non-governmental organizations (NGOs)	- Microfinance NGOs and community-based organizations - Over 50 NGOs in Kenya offer microfinance.	Provides microfinance along with social welfare services. Uses informal community-based systems to deliver credit and savings services.	Varies; some operate as limited companies or building societies. Regulated by Micro Finance Act (2007).
Informal institution			
Rotating savings and credit associations (ROSCAs) and self-help groups (SHGs)	Mutual membership clubs registered as social welfare groups	Members pool resources which are lent to individual members in turns.	Many smaller ROSCAs are not formally registered. SHGs are registered under the Department of Culture and Social Services.

Figure 2-7: Funding from formal and informal institutions (The SEEP Network, 2007b)

Although the availability of energy product loans is still relatively limited, two studies have highlighted programs from select MFIs (Kariuki & Rai, 2010; The SEEP Network, 2007a; The SEEP Network, 2007b)

- *Faulu Kenya*, which partnered with Kenol/Kobil to supply LPG and provided a loan of 10% interest with a 6-12 month repayment period that saw the sale of 5,000 LPG gas cooking units
- *Kenya Union of Savings and Credit Cooperatives (KUSSCO)* procures energy products in bulk and distributes them to individual SACCOs through various lending methodologies, though their energy loans are offered primarily on a declining balance basis
- *Muramati SACCO*, a cooperative with over 15,000 members, launched the Muramati SHS Project under the Photovoltaic Market Transformation Initiative (PVMTI)⁷ to provide credit for the purchase of solar PV systems to be supplied by

⁷ PVMTI is a program of the International Finance Corporation and the Global Environment Facility.

ASP Ltd. The SACCO also has a portfolio that finances mini-hydro installations by funding community based initiatives, with six projects having been funded thus far

- *Small and Micro Enterprise Programme*, which offers a solar PV loan (KES 6,000 for 6 months at 10% interest) and has partnered with Solar World to provide access to solar PV systems and lanterns
- *Githunguri Dairy Farmers Cooperative Society*, a cooperative of 12,000 smallholder dairy farmers which approached *Oikocredit* for a KES 70 million loan payable in 3 years at 10% interest to purchase milk processing machinery that increased their capacity and resulted in higher income such that a portion of the loan was then set aside for the installation of biogas digesters for 500 farmers
- *Kenya Women's Finance Trust*, an MFI with over 200,000 women which initiated a renewable energy programme with funding from the Shell Foundation and supported by IT Power that provided over 5,000 women with LPG for cooking, set up 13 LPG enterprises and installed solar PV systems in 250 households

Other options for end-use level financing include leasing (where the company supplies the technology and charges the consumer a monthly fee in order to recover the upfront investment) and revolving funds (where initial seed funds are used to supply systems and then new loans are continually made using the repayments) (Bhattacharyya, 2013; Gubja et al., 2012).

3. The case of Kilifi - Kenya

Kilifi County is located in the former Coast Province of Kenya, covering a surface area of 12,609.7 km² (KNBS, 2014c). The county is divided into 6 administrative districts (or sub-counties) (Kilifi County Government, 2015). Electorally, there are 7 constituencies and 35 wards (CRA, 2015). Kilifi town serves as the county's administrative capital, and other major urban centers include Malindi, Mtwapa, Mariakani, and Watamu.

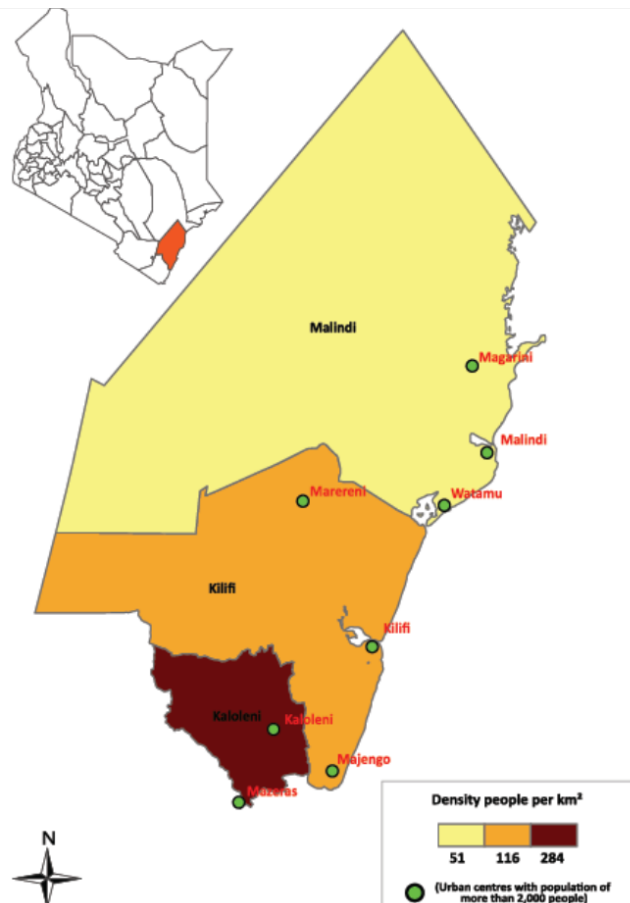


Figure 3-1: Map of Kilifi County (district boundaries) (CRA, 2013)

According to the Kenya Population and Housing Census of 2009, Kilifi County had a population of 1,109,735 (2.9% of the total Kenyan population) in 199,764 households (KNBS, 2014c). The county is young, with children aged 0-14 comprising 47% of the total population, which is slightly more than the national average of 43% (Ngugi, 2013). Approximately 75% of the population is rural (Minnesota Population Center, 2014) and 32.7% of households are female-headed (Ngugi, 2013). The number of people is projected to rise at an annual growth rate of 3.1% to 1,336,590 and 1,466,856 in 2015 and 2017 respectively (Kilifi County Government, 2015).

With 58% of people below the poverty line compared to the 2009 national estimates of 45.2%, Kilifi ranks 14th relative to other counties. The poverty gap (as a percentage of the poverty line) in the county is 31%, placing it 4th nationally. The county also ranks 3rd based on the severity of poverty measure. Kilifi County has the third highest Gini coefficient at 0.565 compared with the national Gini coefficient of 0.445 (Njonjo, 2013).

The mean monthly household consumption expenditure in Kilifi is KES 2,900 per adult equivalent, compared to the national average of KES 3,440. 11% of households have a monthly spending of KES 1,400 or less, while 42% of households have monthly spending of KES 7,200 or more. (Njonjo, 2013) The distribution of household expenditure in Kilifi is used in the cooking model to provide a measure of affordability for fuel services.

County governments, under the directive of national policies, are responsible for regional planning and development: electricity and gas reticulation, control of air and noise pollution, local trade development and regulation, local transportation, and public works (water and sanitation services) (TA & EISA, 2013). The 2014 National Forest Policy will put the implementation of community forest conservation and management, and thus the regulation of the charcoal industry, under county governments (RoK, 2014a; Nation Correspondent, 2015b). The county government is currently promoting the creation of woodlots⁸ to ensure constant and sustainable supply of wood for use as a fuel (Kilifi County Government, 2015).

Figure 3-2 shows the Constituency Development Fund⁹ allocations for Kilifi County from 2005-2012.

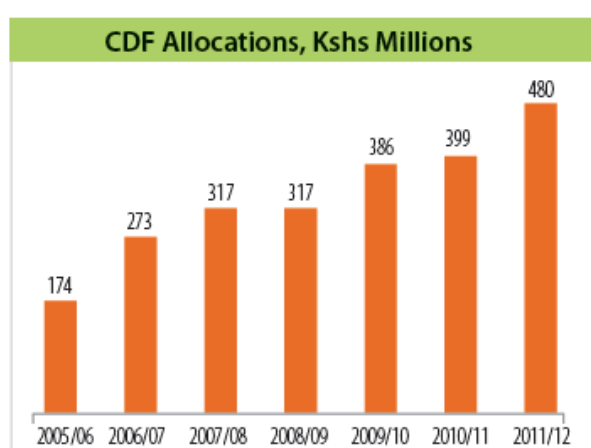


Figure 3-2: Kilifi County Constituency Development Fund Allocations (CRA, 2013)

3.1 Electrification

According to the 2009 census, 16.7% of the population had electricity as their main source of fuel for lighting, compared to 23% nationally (Njonjo, 2013). **Figure 3-3** shows this breakdown, along with the primary sources of lighting for those unelectrified. Electricity use is more common in male-headed households compared to female-headed households at 17.5% and 14% respectively (Ngugi, 2013). The proportion of households using tin lamps (62.6%) is much higher than the national average (38%) (Njonjo et. al, 2013). **Table 3-1** shows the percentage of households with various appliances in the county.

⁸ A woodlot is a piece of land for planting trees to be used as fuel or to provide timber for building materials.

⁹ The Constituency Development Fund (CDF), managed by the Constituencies Development Fund Board, is a fund designed to address poverty at a grassroots level by dedicating a minimum of 2.5% of government ordinary revenue to constituent-level development projects with the aim of equitable distribution of development resources across regions (CDF, 2015).

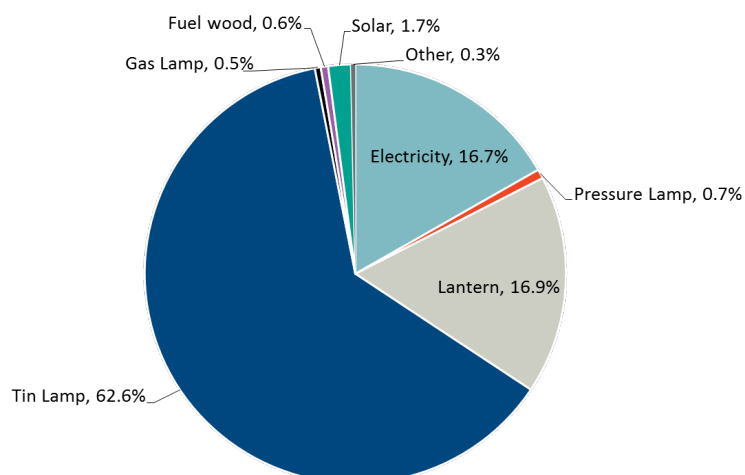


Figure 3-3: Primary source of lighting by household, Kilifi County (Kenya Open Data Network)

Table 3-1: Household appliance ownership, Kilifi County (Minnesota Population Center, 2014)

Appliance	Households (%)
Landline Phone	0.9
Mobile Phone	57.5
Radio	53.6
TV	13.2
Refrigerator	4.4
Computer	2.1
Automobile	2.7

Rural electrification budget allocations from 2005 to 2012, with a decreasing trend from 2010, are shown **Figure 3-4**, and the Kilifi electric grid is in **Figure 3-5**.

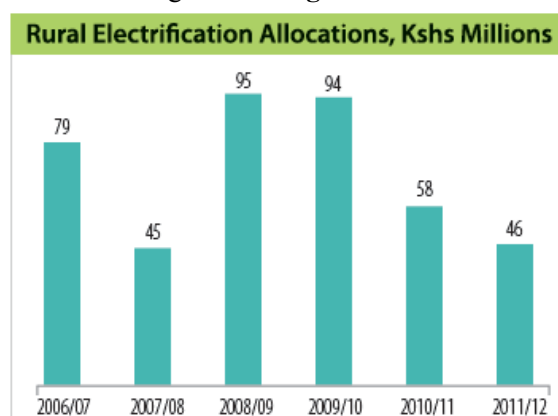


Figure 3-4: Kilifi County Rural Electrification Funding Allocations (CRA, 2013)

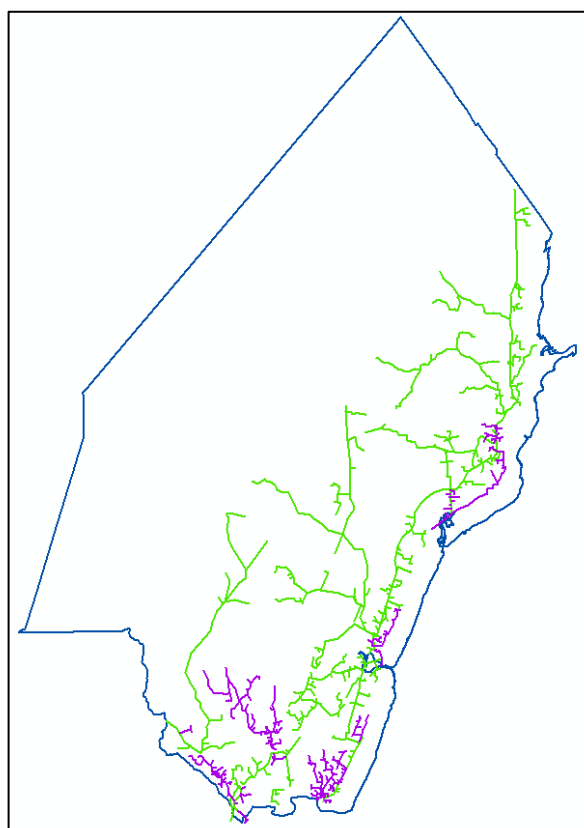


Figure 3-5: Kilifi 33 kV (green) and 11kV (purple) lines

3.2 Cooking

Figure 3-6 shows the breakdown of the primary cooking fuel used in households per the 2009 census. A greater percentage of households (68%) use primitive fuels—wood, animal and agricultural waste—compared to the national average of 64%, although more households (28%) use transition fuels—primarily charcoal and kerosene—than the rest of the country (17%) (Njonjo, 2013).

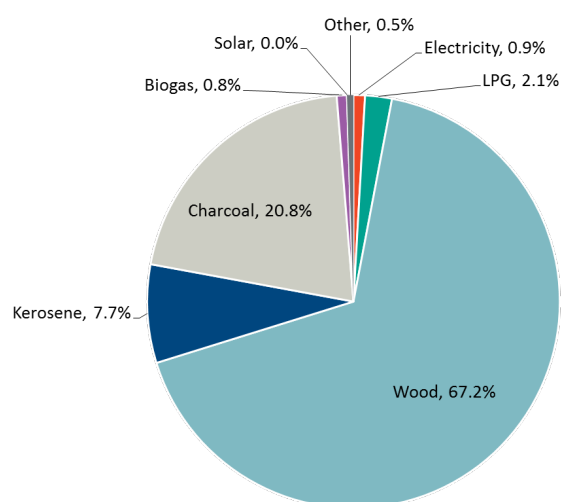


Figure 3-6: Primary cooking fuel by household, Kilifi County (Ngugi, 2013)

The most prevalent cook stove technologies are as shown previously in Chapter 2. A breakdown of the distribution of users of the various cook stoves is in **Table 3-2**. Households

using wood and charcoal as their predominant fuel for cooking were divided evenly among the 6 wood stoves and 2 charcoal stoves respectively.

Table 3-2: Household cook stove use (Minnesota Population Center, 2014)

Appliance	No. of Households
Three Stone Fire (wood)	11,227
Upesi Stove (wood)	11,227
Portable Kuni Mbili (wood)	11,227
Brick Rocket Stove (wood)	11,227
Jiko Poa Stove (wood)	11,227
EnviroFit Stove (wood)	11,227
Traditional Metal Charcoal Stove	5,086
Kenya Ceramic Jiko (charcoal)	5,086
Kerosene Stove	3,562
Biogas Stove	508
LPG Stove	1,042
Solar Cooker	26
Electric Stove	396
Other	127

4. Methodology

Previous chapters have elaborated on relevant work in the energy access space and outlined Kenya and Kilifi's context in this scheme. Here, the methodology and technology toolkit for a comprehensive assessment of the appropriate modes of electrification, heating and cooking for specific countries or regions are described briefly.

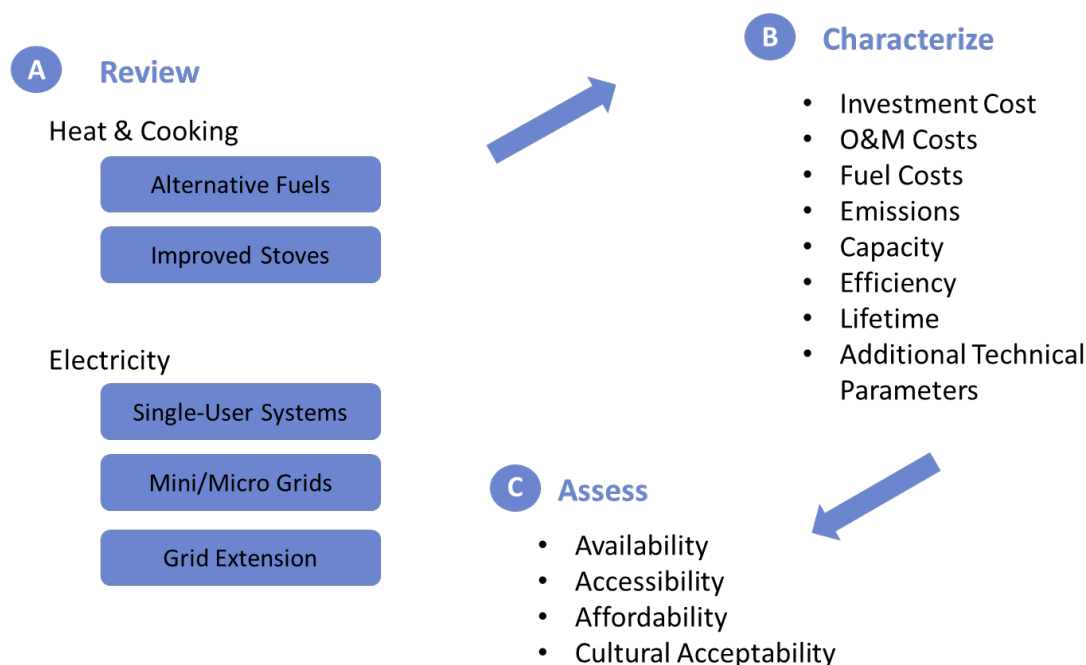


Figure 4-1: Simplified representation of the overarching logic behind the Reference Electrification Model and the Reference Cooking Model

4.1 The Reference Electrification Model

The Reference Electrification Model¹⁰ (REM) supports large-scale electrification planning of both grid extension and off-grid systems by producing near-optimal power system designs, including type, size, and locations of electricity generation, storage, and distribution assets, for a region. The model, developed in the spirit of Reference Network Model¹¹ (RNM) developed at the Instituto de Investigación Tecnológica (IIT) at Universidad Pontificia Comillas in Madrid, could be used by planners (including distribution companies, policy makers, regulators) to estimate electrification costs and appropriate electrification modes (network extension, isolated mini-grids and stand-alone-systems) at a regional level. Additionally, engineers and designers intending to electrify

¹⁰ The description in this section is adapted from the Enel Foundation Working Paper 3: *Appropriate technologies, business models and enabling environment for Universal Access to modern energy services* (July 2014), and the master's thesis *The Reference Electrification Model: A Computer Model for Planning Rural Electricity Access* by Douglas Ellman.

¹¹ (Mateo Domingo, Gomez San Roman, Sanchez-Miralles, Peco Gonzalez, & Candela Martinez, 2011; Peco, 2004; Pieltain Fernandez, Gomez San Roman, Cossent, Mateo Domingo, & Frias, 2011). The RNM model is the outcome of more than a decade of research and successful implementation projects in distribution network planning at IIT. RNM has been used by the Spanish Energy Regulatory Commission to remunerate the distribution companies in Spain, with about 25 million customers, with the agreement and collaboration of these companies. RNM has been used for similar purposes in another countries and in several European research studies.

specific areas could use this tool to facilitate design decisions that appropriately balance level of service and costs.

The REM Process

REM aims to optimize the mix of grid extension, microgrids, and isolated systems to design the appropriate electricity access system for a region. There are a few main steps that must be taken in order to design the power system. These steps could be performed in an automated fashion, in the case of regional planning, or performed with more user-interaction, in the case of design for a specific location. These steps are briefly described below:

- **Division of area into separate analysis regions:** If the area of interest is large (for example, a country) it must first be divided into regions, which can be analyzed and optimized separately, in order to manage computational burden. This could be done, for example, based on demand density or based on distances between demand nodes.
- **Division of analysis regions into electrically isolated clusters:** It must be determined which demand nodes will be electrically connected (into microgrids or grid extension areas) or remain isolated with home systems. This decision could be made flexibly, and re-evaluated based on the outcomes of later design steps.
- **Design of electricity supply for each isolated cluster:** For each cluster, local generation and storage and/or a grid connection must be selected to optimally serve the cluster's demand. This entails selection of supply components from a catalog of components, based on the cluster's demand, energy resources, and costs.
- **Design of distribution network for each isolated cluster:** Given power profiles of demand and generation points, wires, transformers, and other distribution network components are selected at minimum costs, considering technical constraints and losses.
- **Determination of final power system:** Multiple clustering options are explored, and the one that leads to the best power system design is selected. Assessments on which one is 'best' are based on least-cost, though this could also be based on maximizing social welfare or profits, depending on the perspective of the user.

Inputs to REM can be organized into two categories: regional inputs and individual inputs. Regional inputs are data about the region that apply to all or large clusters of buildings or demand points (e.g., houses, schools, etc.) in the region. Individual inputs are data that are specific to each building or demand point.

Regional Inputs

Location of Buildings

In order to develop a detailed system design, it is necessary to know the latitude and longitude of all buildings in the study area. This is the most basic input to the model and this level of specificity is critical for the realistic calculation of technical feasibility, as well as for cost estimation.

The location of the existing distribution feeders and transformers must be obtained for the study area. In the absence of this data, which can be challenging to obtain, it is possible to run the model assuming that no existing distribution grid exists (greenfield mode) or to use GIS to create a proxy distribution system that may approximate what actually exists. Another limitation of modeling the existing grid is that, in general, it changes frequently. A utility may have plans to expand the system or parts of the infrastructure may be destroyed by natural disasters, so it can be difficult to ensure that existing grid data is up to date (unless the distribution utility keeps a complete GIS record of its facilities, which is not the case in the areas of interest for this thesis).

Administrative or other context-relevant boundaries

Buildings should be grouped by the most relevant administrative or context-relevant boundary available. This information can be important both for processing a large dataset by analyzing it in smaller chunks and/or for ensuring that the results are produced subject to administrative or other organizing constraints. For example, breaking the analysis of a district into its sub-districts can ensure that a single system does not cross over jurisdictional boundaries where political interests, rules, and requirements, as well as citizen preferences may differ. More granular administrative boundaries can be also useful, like blocks, villages or wards (in India).

Unelectrified households

Amongst all the buildings in a region, it is necessary to determine which buildings are currently connected to the existing grid or are electrified already by other means, and which buildings require electrification. The model does not make determinations about whether existing grid infrastructure is cost effective. Buildings that are classified as electrified may not be considered in the model, which will be the case for the examples described in this document. Grid extension may require joint consideration of upstream network reinforcements (outside of REM) that are needed for the existing electrified and newly electrified customers.

Energy resources

The availability of different energy resources (e.g., solar irradiation, diesel availability, biomass resources, potential sites for mini-hydro plants) in a given area is necessary in order to determine the suitability of different types of generation. This data must be aggregated at the relevant unit of analysis, whether that is a value for each building, a value for a given area within the study region, or a single value for the entire study region.

Cost of Non-Served Energy (CNSE)

To compare costs between a grid extension and an off-grid system it is necessary to know the cost, to consumers, of energy that is not served in order to account for the reliability of each system (or unreliability, as the case may be). This concept is actually quite subjective, but is intended to represent the cost (i.e., the loss of utility) incurred by consumers when there is no electricity at a time when they were planning to use it. REM requires two values for CNSE, one for essential load and another for nonessential load. The CNSE value for essential load should be higher than the CNSE value for nonessential load in order to represent the greater

cost (equivalently, loss of utility) to the consumer for not meeting the most valuable demand. CNSE is also needed to size the generation source in a microgrid so that a theoretically optimal trade-off is reached between cost of supply and quality of service. There could be multiple ways of arriving at a value for CNSE, but one way of calculating CNSE value is to determine the cost of an alternative energy solution (e.g., kerosene) that might be used when electricity is not available and adopt that value as a proxy, possibly adjusted by some arbitrary factor to account for the inconvenience of procuring the alternative energy source or to account for the type of demand not served (i.e., essential or non-essential).

Generation equipment catalog

A catalog of generating equipment to be considered, its specifications, and the cost of each piece of equipment is necessary in order to create a detailed system design and effectively compare costs between different systems and designs. Generation equipment includes components like solar panels, batteries, diesel generators, inverters, and other power electronics. Although it is probably impossible to collect an exhaustive list of all possible generation components in use throughout a region (e.g., there could be several models of solar PV panels), that is not a problem as long as there is a representative specification for each type of equipment that should be considered.¹²

Network technical requirements and catalog

This data set includes typical load voltage, generator voltage, network lifetime, reliability targets, and cost of network losses experienced in the region being studied or used in the Reference Network Model catalog. The catalog also contains equipment specifications, such as the technical parameters, costs, and failure rates of conductors, transformers, and substations.¹³

Reliability of the existing grid

In order to provide a more informed comparison between grid extension and off-grid systems it is necessary to know the reliability of the supply of electricity from the existing grid (i.e., the number of hours per year the grid is expected to be supplying electricity and when). This value can be expressed as one overall percentage or broken up into a percentage for off-peak reliability and peak reliability in order to reflect, for instance, the fact that in some areas the outages might be more likely to occur during peak demand hours. Reliability is also important to the concept of CNSE.

Price of diesel

Diesel generator sets may be used as a primary or supplementary source of electricity. Some microgrids also use a mix of solar and diesel generation in order to meet demand in areas where solar irradiation is more volatile. For this reason, it is necessary to model the price of diesel for generation. Estimating the cost of diesel is not so simple, since the official cost per liter does not take into account several associated costs, such as the cost of transporting the

¹² REM can be used to design optimally just one microgrid for a specific village, for instance. In that case the level of accuracy in the catalog of equipment has to reflect a satisfactory level of reality.

¹³ For more information see Ellman, Douglas. 2015. "The Reference Electrification Model: a Computer Model for Planning Rural Electricity Access." Master's Thesis, MIT.

diesel to a rural marketplace, the cost of traveling to purchase diesel, as well as the cost of storing and protecting such a desirable product.

Discount rate

A discount rate is necessary to determine the net present value of a given project to the owner of the assets (e.g., the project developer). Depending on the planner running the model, the discount rate could be adjusted to reflect the assessed risk of power projects in a region, estimated time needed to recover the up-front investment, and several other factors.

Individual inputs

Classification of buildings

If data are available, buildings can be categorized by customer type (e.g., house, school, hospital, etc.), but this is not strictly necessary for the model to produce preliminary results. The added specification of customer types makes it possible to specify different electricity demand profiles, since households typically have different electricity demand profiles than public buildings, for example.

Characterization of demand

Following the classification of buildings, the demand for each building needs to be characterized. To design electrification solutions for unelectrified buildings it is necessary to estimate how much electricity each building might consume if it had access to electricity. Since the model will try to meet specified demand at the lowest techno-economic cost, more detail about demand at each individual load point is likely to have an influence on the results. Characterizing demand requires data about either a) the hourly demand profile of similar buildings in a similar context (which includes affordability, geographical proximity, type of economic activity, type of house, etc.) that do have access to electricity, b) constructing an hourly demand profile from a reasonable inference about what types of appliances the occupants of the building might use and how often, or c) setting a demand target. For the second method, characterizing demand may also require weather data and the timing of sunrise and sunset in the region in order to construct a more representative hourly demand profile. Once the demand profile is constructed, it must be classified into one of two tiers: 1) essential load (e.g., lighting) or 2) nonessential load (e.g., television).

The REM output consists of a set of detailed network and generation design files which are produced by taking into account individual demand, energy resources, quality of service, and existing infrastructure for all the clusters in a region. The network files contain both geographic location and technical characteristics of the network equipment, and the generation files contain cost (investment, operation, maintenance and replacement) and performance estimates (technology, component sizes, generation, and emissions). As a part of post-processing, a financial model is under development for REM that will look at various business models for operation to get values for important economical parameters such as tariff, subsidy, and rate of return on investment.

4.2 The Reference Cooking Model

The Reference Cooking Model (RCM) is a tool meant to provide an estimate of the cost of providing access to cooking fuels with the goal on minimizing environmental impact. The SE4all multi-tier framework has been taken as the basis for evaluating various household cooking solutions. The framework allows for determining the overall technical performance of the primary cook stove while taking into account the conformity, convenience, and adequacy (CCA) attributes which touch upon the issues of maintenance, convenience, social and cultural fit, and availability and affordability of fuel. The overall access to modern cooking solutions can then be determined based on the total number of households at various levels of service, and the associated environmental impact.

The RCM Formulation

A schematic of the logic behind RCM is shown below.

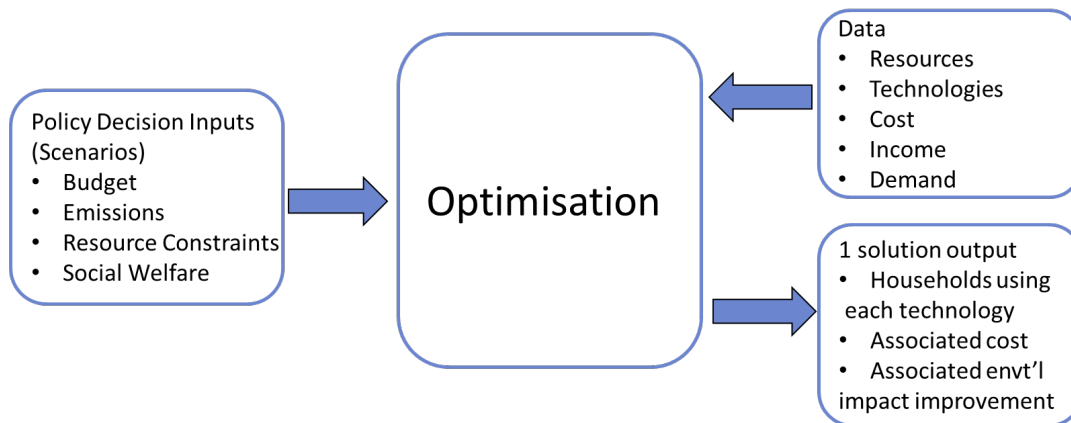


Figure 4-2: Schematic of the Reference Cooking Model

The main factors under consideration are:

- The number of households in each tier (associated with the use of certain technologies) which varies and is dependent primarily on location and income
- The cost of cooking options which increases with the use of cleaner fuels and more efficient stoves
- The associated health impact of cooking options which correspondingly decreases when moving up the tier

The energy flow from resources to final useful energy is depicted below. In the case of biomass, for example, wood (as the initial resource, r) can either be burned directly, or converted into charcoal or briquettes (fuel, f), each of which can then be used in different types of cookstove technologies, t , to be converted into heat. The use of a certain technology is associated with an amount of final useful energy (UE) given a specific amount on initial resource use, r , and can then be mapped onto a tier category based on the technology's characteristics.

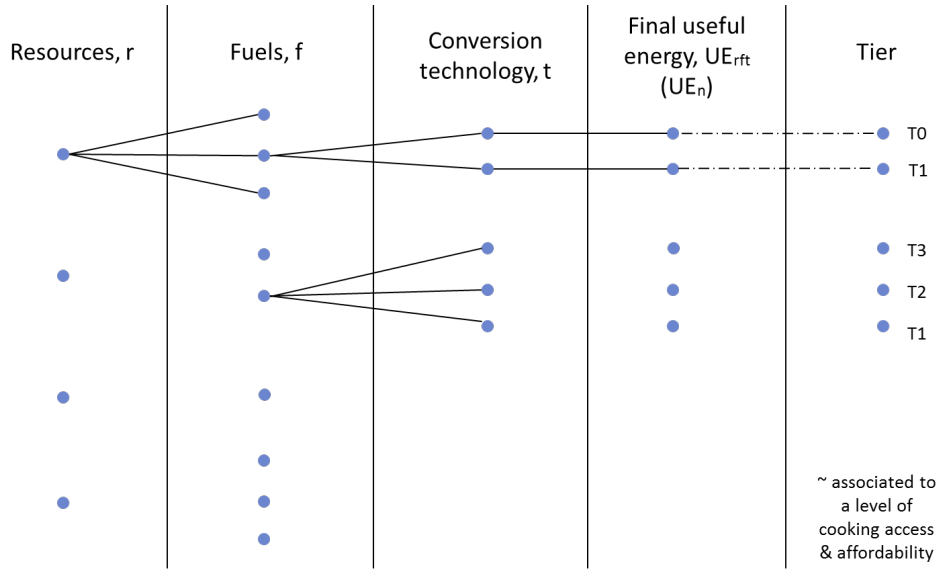


Figure 4-3: Energy flows from resources to final useful energy

Viable transitions, X_{nm} , from an initial state, n , associated with a corresponding set of resource, fuel type, and technology to a final state, m , are then identified based on the relevant country situation.¹⁴

Parameters

For each district, d :

- Define the resource (r), fuel (f), & conversion technology (t) resulting in useful energy UE_{rftd} for one household
- For each UE_{rftd} , there is a resource utilization R_{rftd}
 - Define $RMAX_d$: the max amount of resource (r) that can be used to obtain $\sum_{ft} UE_{rftd}$

r , f , t are mapped onto N states ($UE_{rftd} \rightarrow UE_{nd}$), which can be classified into tiers for reporting purposes.

For each UE_{nd} :

- ‘envtl’ impacts, EI_{nd}
 - Indoor pollution ~ health impact (& may be emissions?)
 - Deforestation
- Costs
 - Annuity of investment cost, FC_{nd}
 - Annuity of fuel cost, VC_{nd}
- Inconvenience

¹⁴ The logic behind identifying, which transitions are, viable will vary depending on the reality of the on-the-ground situation. Transitions that can be immediately eliminated are those that would move a household to a lower level of access. Other possible transitions, for example, could be based on government actions and the intended effects that a government wants a particular subsidy to have.

- Safety

The ‘envtl’ improvement of a transition for a household is given by:

$$\sum_e (EI_{md} - EI_{nd})$$

Transition cost depends only on the final state, although this is a function of the assumptions made about the available budget and any previous subsidies.

The ‘envtl’ impact improvement of a transition depends on the initial & final state.

Define affordability, A_{nd} : states $n = 1, \dots, N$ associated with each state; all households in a given state are initially assumed to have the same level of affordability (at the very least can afford the amount they currently spend on energy for cooking). It can be the case that there are multiple levels of affordability for households using a given technology. In this case, affordability will be defined as A_{nid} for states $n = 1, \dots, N$ and income groups $i = 1, \dots, I$. The affordability is multiplied by a weighting factor between 0 and 1 that is assigned to each technology and which is based on the consumer preferences for each cook stove type, giving the willingness to pay, W_{nid} , for states $n = 1, \dots, N$ and income groups $i = 1, \dots, I$.

Variables

$$H_{mnid}^{15}$$

where:

H is the no. of households

n is the initial state; $n = 1, \dots, N$

m is the final state; $m = 1, \dots, M$

i is the income group; $i = 1, \dots, I$

d is the district

Also, define H_{md} : the number of households in each state at the end:

$$H_{md} = H_{m0d} + \sum_n H_{nmd} - \sum_k H_{mkd}$$

Objective Function

- Budget: B for one year in new plan¹⁶

$$- \text{Define household deficit, } D_{mid} = \max [0, FC_{md} + VC_{md} - W_{mid}]$$

¹⁵ A different formulation where the decision variable does not depend on the transition from one state to another but is, instead based on the number of household H_{nd} in the various final states is also possible. Choosing which formulation is better depends on the number and complexity of constraints required, in that, while the latter formulation will have a lower number of decision variables, it must also be specified that certain states can only be reached in a certain ways. In the formulation above, possible transitions are already pre-defined by the chosen state variables.

¹⁶ For the budget, we will ignore on-going plans and subsidies.

- The deficit represents the amount over a household's affordability for a given cooking option for which the budget will be used to subsidize the associated costs.

$$\min \sum_{states} (no. \text{ hh that change}) \cdot (deficit)$$

$$\min \sum_{n \ i \ d} H_{mnid} \cdot D_{mid}$$

Constraints

- Resources: for a given district, d :

$$\sum_{f \ t} H_{md} \cdot R_{rftd} \leq RMAX_d$$

- 'Environmental' impacts targets: the target level of pollution reduction, P_d , defined as a percentage of the current level of pollution

$$\sum_{n \ d} H_{mnid} \cdot \sum_e (EI_{md} - EI_{nd}) \geq P_d$$

Inputs

1. Resources availability
2. Household energy demand for cooking
3. Number of households in rural vs. urban areas
4. Household income levels & consumer preferences (and, therefore, their willingness to pay)
5. Number of households using various types of cooking technologies (and, therefore, their initial tier of access)
6. For various technology types:
 - a. Fuel and stove conversion efficiency
 - b. Cost
 - i. Fuel
 - ii. Appliance
 - c. Environmental impact (deforestation, emissions)
 - d. Health impact (premature deaths, respiratory illnesses)
 - e. Safety (fire risk, burns)
 - f. Conformity
 - g. Inconvenience
 - h. Adequacy

This analysis includes only fuel cost, fuel and stove conversion efficiency, and particulate emissions (as a proxy for health impacts).

Output

For a given geography/region:

1. Number of households using each cooking technology (and correspondingly, in each tier)
2. Cost of achieving the specified level of access
3. The environmental impact improvement obtained from the overall transition

5. Results and Discussion

Previous chapters outlined the methodology, model design, and input parameters used in REM and RCM. This section highlights key results from an application of the proposed technology toolkit to Kilifi County.

5.1 Electrification

The district of Kaloleni was chosen for demonstrating the potential of REM in electrification planning for large areas. **Figure 5-1** shows the location of Kaloleni district in Kilifi County, and the existing electric distribution network.

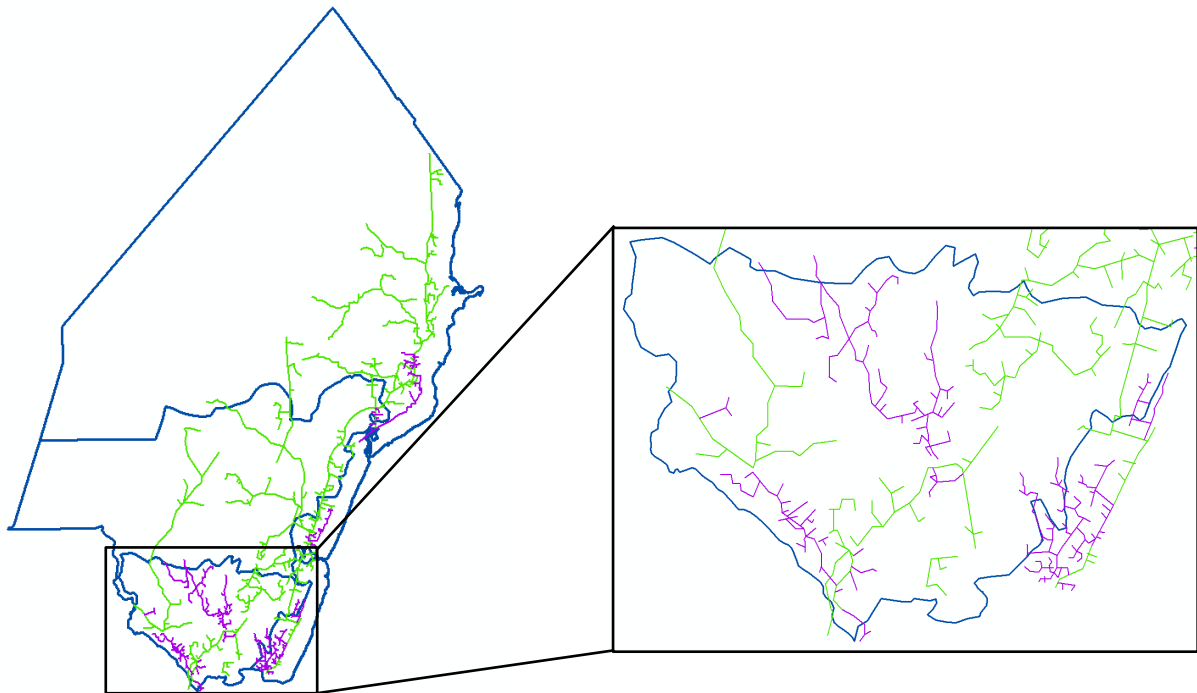


Figure 5-1: Kaloleni electric grid (33 kV lines in green and 11kV lines in purple)

Customer locations were determined using an algorithm that extracts buildings from satellite data (**Figure 5-2**). 8% of households cited electricity as their main source of lighting in the 2009 census, and thus, are assumed to be electrified. REM uses buffer around existing grid lines to assign the buildings closest to the medium voltage 11 kV lines as electrified. These customers are then removed from the set of identified buildings to leave only unelectrified customers for consideration in the model. In Kaloleni district, there are 42,755 unelectrified households for which REM is used to design electrification solutions.



Figure 5-2: Unelectrified buildings identified in Kaloleni district (total of 42,755)

It is also assumed that all the buildings represent a one-household residence, and that all households have a similar demand profile (**Figure 5-3**). The average peak demand in this scenario is ~ 75 W represented by basic electrical appliances such as light bulbs, cell phone chargers, radios, televisions and fans. This is the demand profile for base scenario.

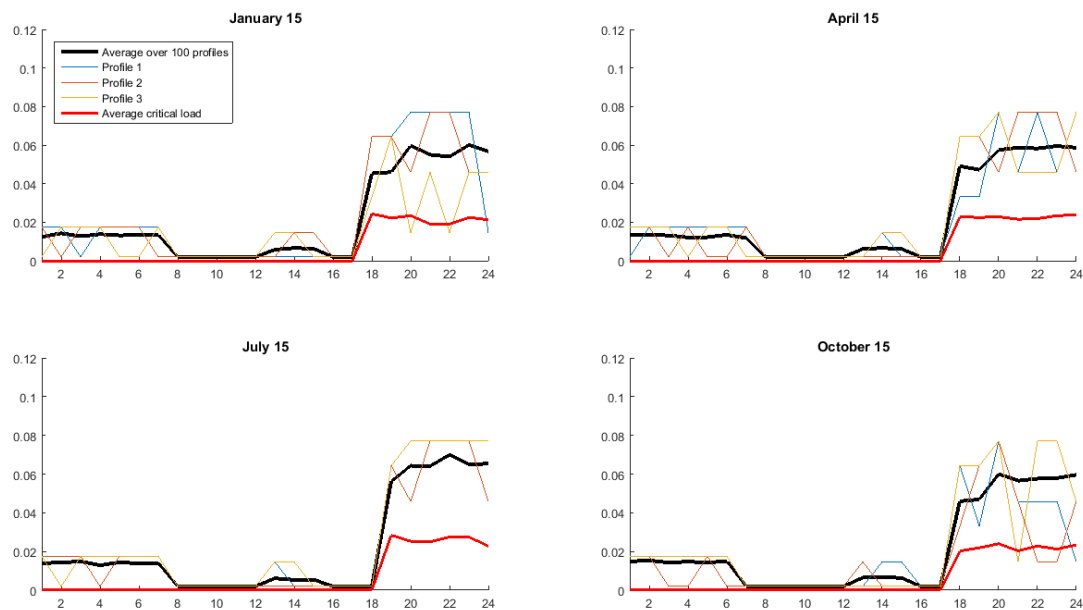


Figure 5-3: Demand profile for residential household for REM

Results for REM scenarios are presented below. The following are the main assumptions made which are common throughout all scenarios:

- Cost of energy supply for the grid: \$0.08/kWh
- Cost of non-served energy (CNSE)-normal: \$0.75/kWh; CNSE-critical: \$10.00/kWh
- Network lifetime: 40yrs
- Distribution system losses: 5%
- Discount rate: 10%

- Demand growth rate: 1%
- Final year for generation design: 5
- Estimated solar PV output power data of a 1kW PV array for one year in Mombasa

The input parameters can be tuned to do a comparative study between different scenarios. The scenarios discussed below differ in the values assigned to grid reliability, the price of diesel, and the energy demand. The idea behind running these scenarios was to show the potential for REM as a powerful tool that could be used to analysis different situations according to reality on the ground. In case of the first 3 scenarios, the grid reliability is varied to show how it might affect the overall electrification solution. By changing price for diesel in scenario 4 and 5, REM looks at how this affects the off-grid generation options. Lastly, by changing the overall demand, REM analyzes variation in the final electrification solutions. With the last scenario again we change grid reliability and compare with scenario 6 with higher demand.

	Grid reliability (%) ¹⁷	Electricity Demand	Price of Diesel (\$/L)
Scenario 1	93.75	Base case	1.00
Scenario 2	50	Base case	1.00
Scenario 3	100	Base case	1.00
Scenario 4	93.75	Base case	2.00
Scenario 5	93.75	Base case	10.00 (Solar only)
Scenario 6	93.75	~5x Demand	1.00
Scenario 7	93.75	~10x Demand	1.00
Scenario 8	100	~5x Demand	1.00

The results of each scenario are presented as maps in **Figures 5-4** through **5-9**. Several points to note on the discussion of these results:

- Annual financial cost includes the following:
 - For grid connection, the cost of energy acquisition and network extension to the households¹⁸
 - For network extension, the cost of investment, operation and maintenance cost and replacement costs are included in the annual financial cost
 - For off-grid systems:

¹⁷ Communication from KPLC indicated that the average reliability for MV lines in Kenya was approximately 22.5 hours per day, which translated into 93.75% grid reliability for the purposes of modeling in REM.

¹⁸ The financial costs for grid extension do not include costs for upstream reinforcements of generation and the transmission to account for the increase in the number and demand level of households connected to the grid.

- The annuity of investment costs for PV, batteries, diesel generator, inverter, and charge controller
- The annual operation and maintenance costs for the PV array, batteries, diesel generator, inverter, and charge controller
- The diesel fuel cost for the final year
- In the case of microgrids, the cost of the network for the microgrid connections
- When averages are discussed for each type of connection (grid extension, microgrid, stand-alone system) in each scenario, the numbers presented refer to the average over the number of customers supplied by that particular system.

Scenario 1 (grid reliability 93.75%; diesel price \$1/liter: “BASE SCENARIO”)

This scenario is intended to best represent the current scenario for Kaloleni with the current grid reliability, and fuel prices. In this scenario, the largest percentage of unelectrified households (97%) were assigned to microgrids, while 2% of the unelectrified households were assigned to grid extension and less than 0.01% of isolated customers were assigned to a stand-alone system (SAS).

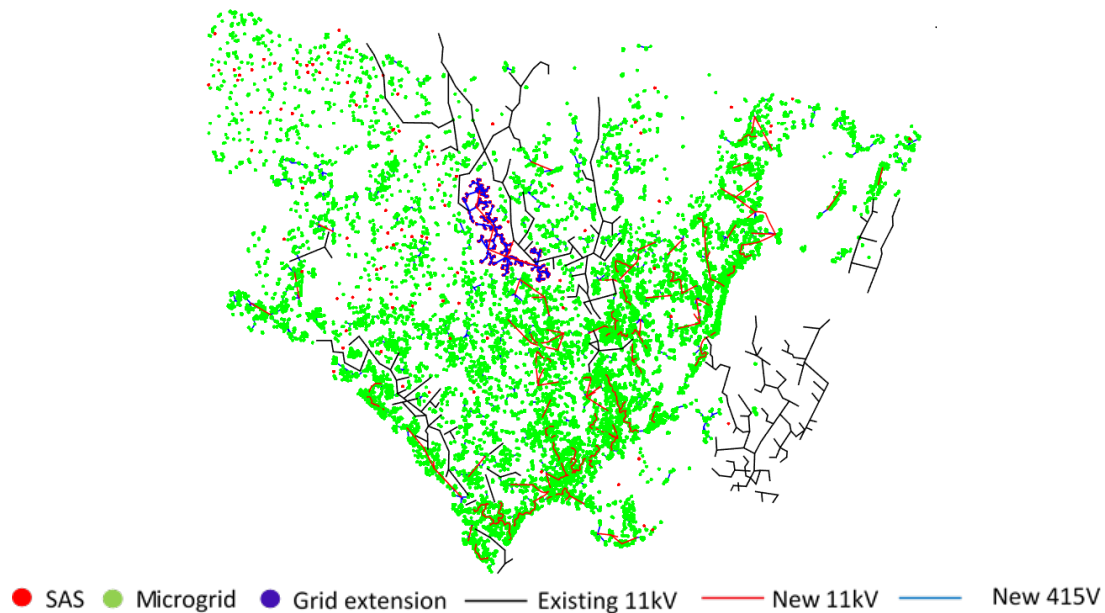


Figure 5-4: REM result for scenario 1 showing different electrification solutions

The average annual financial cost of grid connection per household connected to the grid was \$88.84 while the average cost per kWh of demand served with the grid was \$0.46.

There were a total of 1,585 microgrids, powered by PV panels and diesel generators, ranging in size from 2 to 3,662 households connected to a single system. The average size of a microgrid was 26 households per microgrid. The average financial annual cost of a microgrid connection per household was \$108.80 and the average cost per kWh of demand served with a microgrid was \$0.62. Meanwhile, the microgrids served about 90% of the total demand. This value is calculated by taking the ratio of the total demand met by microgrids, and the total electricity demand from the customers of the microgrids. **Figure 5-5** shows the distribution of the fraction of the demand served by microgrids. Even though it shows more

than 1200 microgrids serving at the rate of 40%, larger microgrids are more reliable (~100%), primarily due to the presence of diesel generators. Regarding the generation design, for smaller microgrids (<10 customers), PV and battery combination supported most of the critical loads to provide the least cost solution. For larger microgrids, diesel generator provided higher reliability.

For the 98 isolated households, the average annual financial cost per household was \$127.19 for a system consisting of a 250W solar panel, and a 0.48 kWh battery bank in each household. The average cost per kWh of demand served was \$1.80. The solar home systems served approximately 34% of the total demand per household.

Table 5-1: Results summary for Scenario 1

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	41,648	98	1,009	42,755
Fraction of Customers	0.97	0.00	0.02	1
Average Financial Cost Per Customer (\$/yr)	108.80	127.19	88.84	108.37
Average Non-served Energy Cost Per Customer (\$/yr)	15.15	102.75	40.92	15.96
Total Financial Cost (\$/yr)	4,531,283	12,464	89,640	4,633,388
Total Financial and Non-served Energy Cost (\$/yr)	5,162,297	22,534	130,928	5,315,759

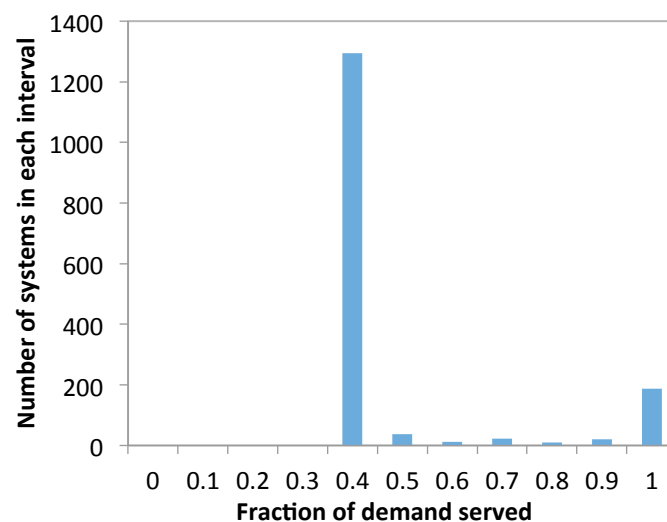


Figure 5-5: Fraction of demand served (majority of microgrids are serving ~ 40% of the demand i.e. mostly critical loads)

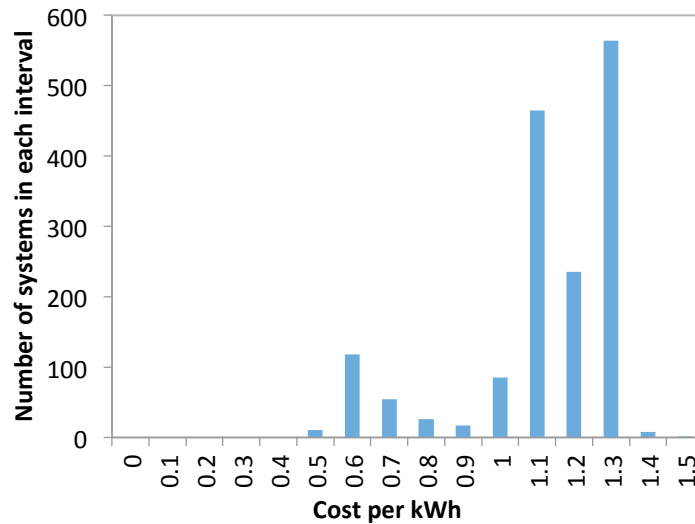


Figure 5-6: Electricity cost per kWh for microgrids

Scenario 2 (grid reliability 50%; diesel price \$1/liter)

This scenario represents a situation where the grid connection is 50% reliable. This variation causes all households to have off-grid solutions. In this scenario, almost all households, ~100%, were assigned to microgrids and less than 0.01% of isolated customers were assigned to stand-alone systems.

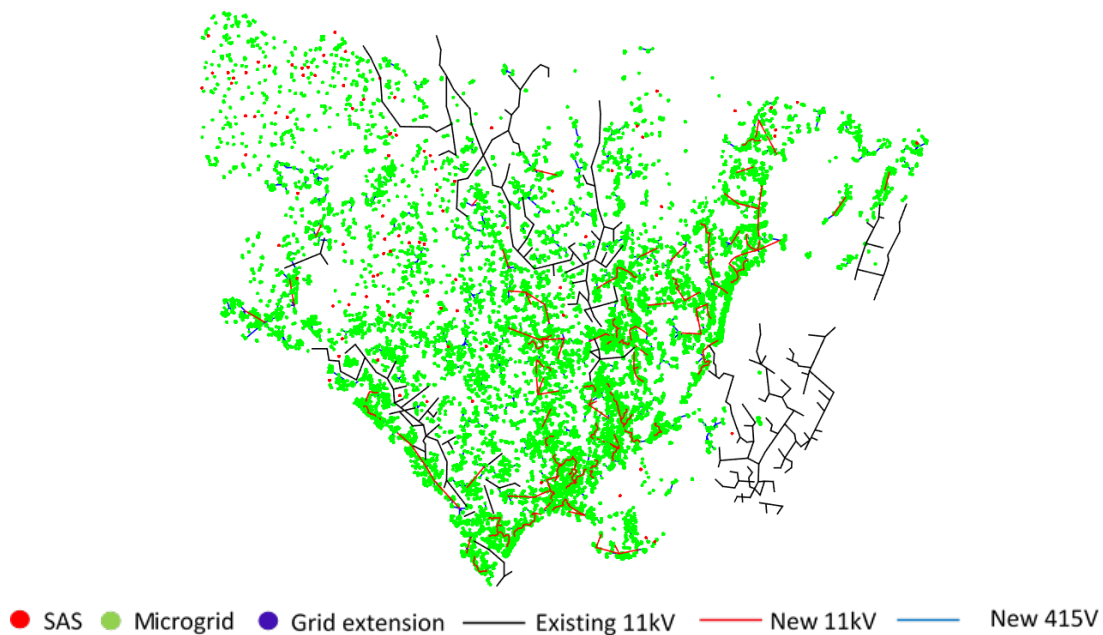


Figure 5-6: REM result for Scenario 2 showing different electrification solutions

There were a total of 1,629 microgrids, ranging in size from 2 to 3,639 households connected to a single system, although the average was around 26 households per microgrid. The average financial annual cost of a microgrid connection per household was \$108.64 and the average cost per kWh of demand served with a microgrid was \$0.62. The microgrids served about 90% of the demand for each household, on average.

For the 98 isolated households, the average annual financial cost per household was \$127.19 for a system consisting of a 250W PV array and a 0.48 kWh battery bank in each household.

The average cost per kWh of demand served was \$1.80. The home systems served 34% of demand per household.

Table 5-2: Results summary for Scenario 2

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	42,657	98	0	42,755
Fraction of Customers	1.00	0.00	0	1
Average Financial Cost Per Customer (\$/yr)	108.64	127.19	N/A	108.68
Average Non-served Energy Cost Per Customer (\$/yr)	15.42	102.75	N/A	15.62
Total Financial Cost (\$/yr)	4,634,068	12,464	0	4,646,532
Total Financial and Non-served Energy Cost (\$/yr)	5,292,038	22,534	0	5,314,573

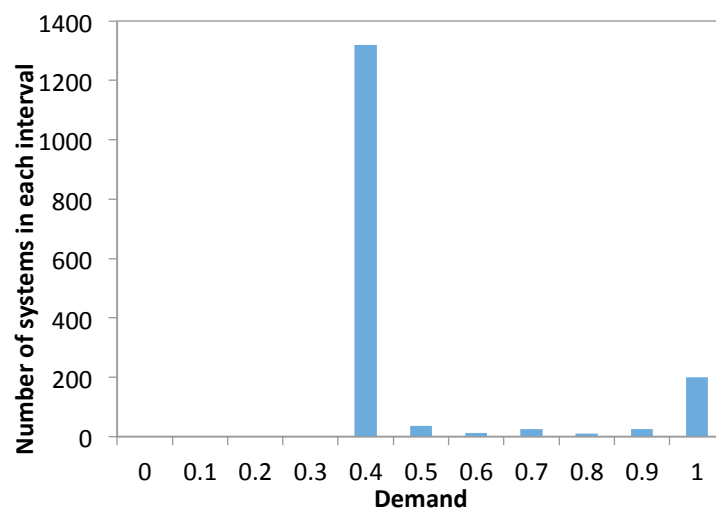


Figure 5-7: Fraction of demand served by microgrids

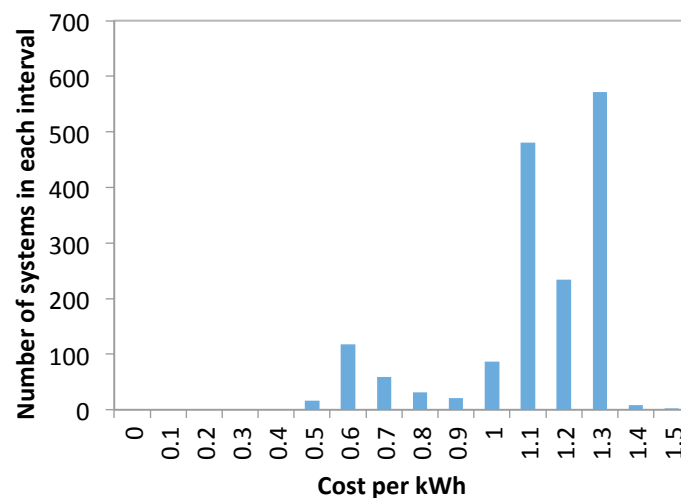


Figure 5-8: Electricity cost per kWh for microgrids

Scenario 3 (grid reliability 100%; diesel price \$1/liter)

This scenario represents a situation where the grid connection is 100% reliable. This variation causes most of the households to have grid extension solutions. In this scenario, the largest proportion of households (84%) was assigned to grid extension, approximately 16% were assigned to microgrids, and less than 0.01% of isolated customers were assigned to stand-alone systems.

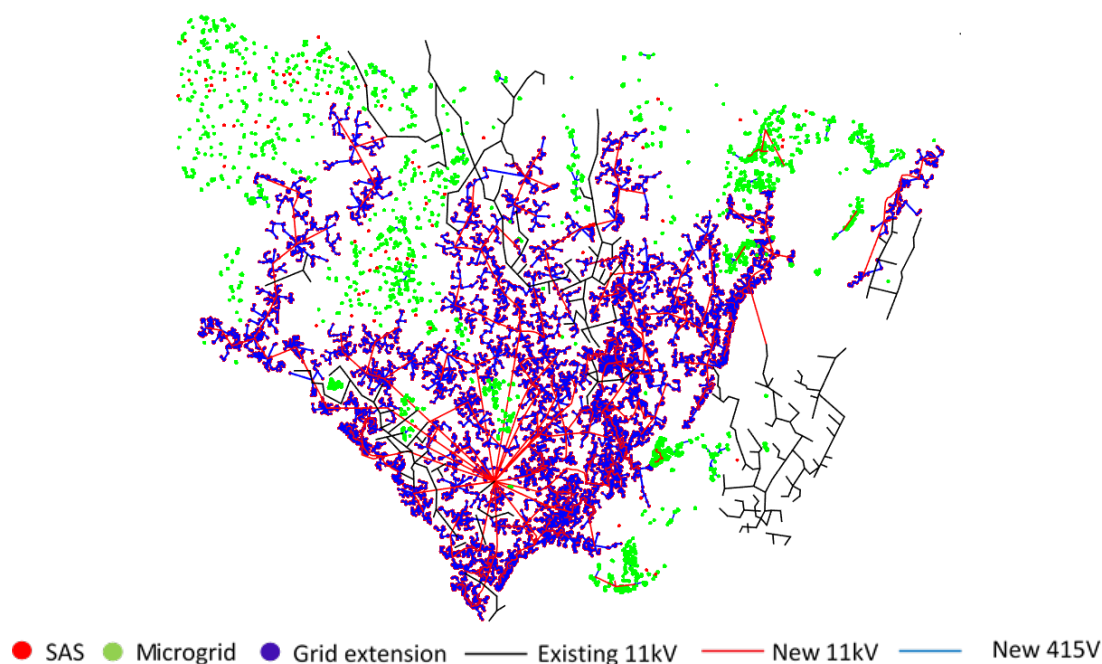


Figure 5-9: REM result for Scenario 3 showing different electrification solutions

The average annual financial cost of grid connection per household connected to the grid was \$90.22 while the average cost per kWh of demand served with the grid was \$0.43.

There were a total of 681 microgrids, ranging in size from 2 to 403 households connected to a single system, although the average was around 10 households per microgrid. The average financial annual cost of a microgrid connection per household was \$104.92 and the average cost per kWh of demand served with a microgrid was \$0.75. The microgrids served about 77% of the demand for each household, on average.

For the 64 isolated households, the average annual financial cost per household was \$127.29 for a system consisting of a 250W PV array and a 0.48 kWh battery bank in each household. The average cost per kWh of demand served was \$1.80. The individual system served 34% of demand per household.

Table 5-3: Results summary for Scenario 3

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	6,685	64	36,006	42,755
Fraction of Customers	0.16	0.00	0.84	1
Average Financial Cost Per Customer (\$/yr)	104.92	127.29	90.22	92.58

Average Non-served Energy Cost Per Customer (\$/yr)	34.91	102.97	0.00	5.61
Total Financial Cost (\$/yr)	701,413	8,146	3,248,499	3,958,059
Total Financial and Non-served Energy Cost (\$/yr)	934,793	14,737	3,248,499	4,198,029

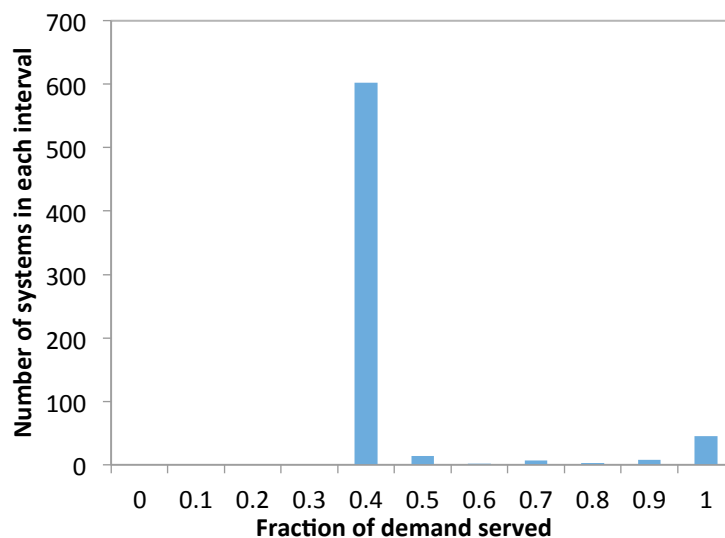


Figure 5-10: Fraction of demand served by microgrids

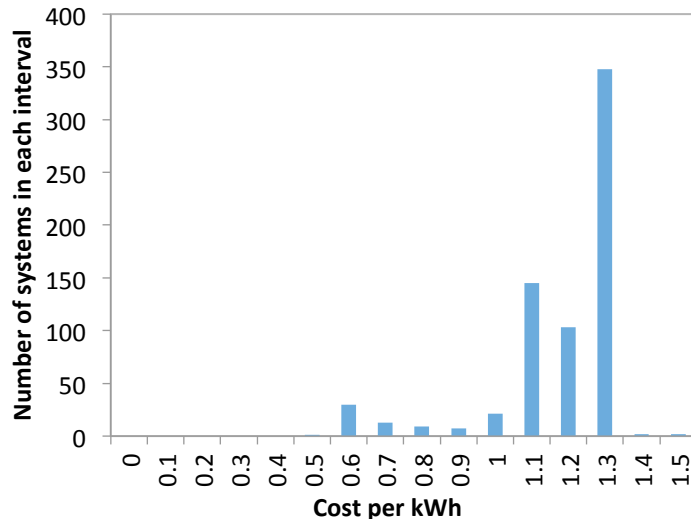


Figure 5-11: Electricity cost per kWh for microgrids

Table 5-4 shows the comparison between the above scenarios, where the grid reliability is varied from 50% to 100%. As expected, with highly reliable grid, grid extension is the least cost solution to meet most of the electricity demand. When the grid reliability is down, microgrids become the preferred solution since the cost of non-served energy with grid extension becomes very large. Such type of dependence on grid reliability is important to note mostly in developing countries such as India where many times the reliability of the national grid is very poor (40-60%). In such cases, microgrids become economically viable solution for electricity access. As we see, in the case of Kenya, particularly for Kilifi, grid

conditions are fairly good. Thus for majority of the population without access to electricity, grid extension is possibly the best solution.

Table 5-4: Summary of cost and performance results by system for scenarios varying grid reliability

	Scenario 2 (50%)	Scenario 1 (93.75%)	Scenario 3 (100%)
<i>Grid Extension</i>			
Annual Financial Cost per Household	N/A	\$88.84	\$90.22
CNSE per Household	N/A	\$40.92	\$0.00
Percentage of Demand Served	N/A	93.8%	100%
Cost per kWh	N/A	\$0.46	\$0.43
<i>Microgrids</i>			
Number of Households per Microgrid	26	26	10
Annual Financial Cost per Household	\$108.64	\$108.80	\$104.92
CNSE per Household	\$15.42	\$15.15	\$34.91
Percentage of Demand Served	89.8%	89.9%	77.2%
Cost per kWh	\$0.62	\$0.62	\$0.75
<i>Isolated Home Systems</i>			
Annual Financial Cost per Household	\$127.19	\$127.19	\$127.29
CNSE per Household	\$102.97	\$102.75	\$102.97
Percentage of Demand Served	33.9%	33.9%	33.9%
Cost per kWh	\$1.80	\$1.80	\$1.80
Total Annual Financial Cost	\$4,646,532	\$4,633,388	\$3,958,059
Total Annual Financial & NSE Cost	\$5,314,573	\$5,315,759	\$4,198,029

Scenario 4 (grid reliability 93.75%; diesel price \$2/liter)

This scenario showcases how fuel prices, diesel in this case, could influence the choice of electrification mode. As the diesel price increases, one would expect off-grid systems to be more expensive. Thus, when comparing with scenario 1, we see more grid extension customers. In this scenario, the largest percentage of households, 75%, were assigned to grid extension, while 25% were assigned to microgrids, and less than 0.01% of isolated customers were assigned to a SAS.

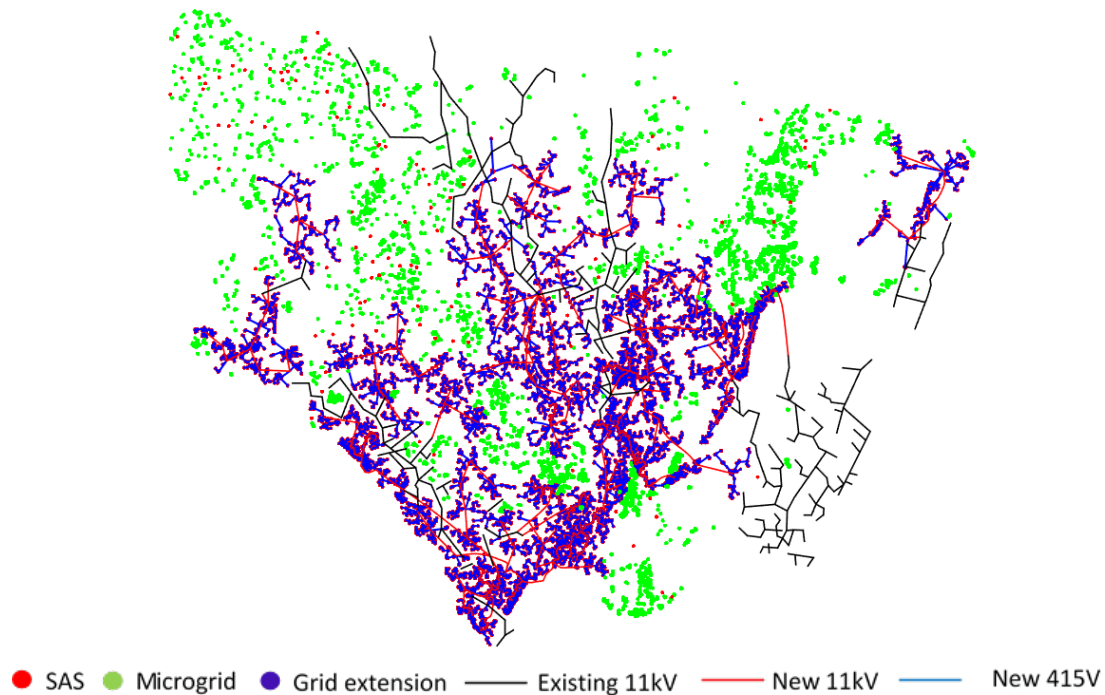


Figure 5-12: REM result for Scenario 4 showing different electrification solutions

The average annual financial cost of grid connection per household connected to the grid was \$85.36 while the average cost per kWh of demand served with the grid was \$0.43.

There were a total of 1,621 microgrids, ranging in size from 2 to 25 households connected to a single system, although the average was around 7 households per microgrid. The average financial annual cost of a microgrid connection per household was \$72.49 and the average cost per kWh of demand served with a microgrid was \$1.03. The microgrids served about 34% of the demand for each household, on average.

For the 101 isolated households, the average annual financial cost per household was \$127.19 for a system consisting of a 250W PV array and a 0.48 kWh battery bank in each household. The average cost per kWh of demand served was \$1.80. The individual system served 34% of demand per household.

Table 5-5: Results summary for Scenario 4

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	10,729	101	31,925	42,755
Fraction of Customers	0.25	0.00	0.75	1
Financial Cost Per Customer (\$/yr)	72.49	127.19	85.36	82.23
Non-served Energy Cost Per Customer (\$/yr)	102.76	102.75	40.90	56.57
Total Financial Cost (\$/yr)	777,72	12,846	2,725,274	3,515,843
Total Financial and Non-served Energy Cost (\$/yr)	1,880,247	23,224	4,031,139	5,934,611

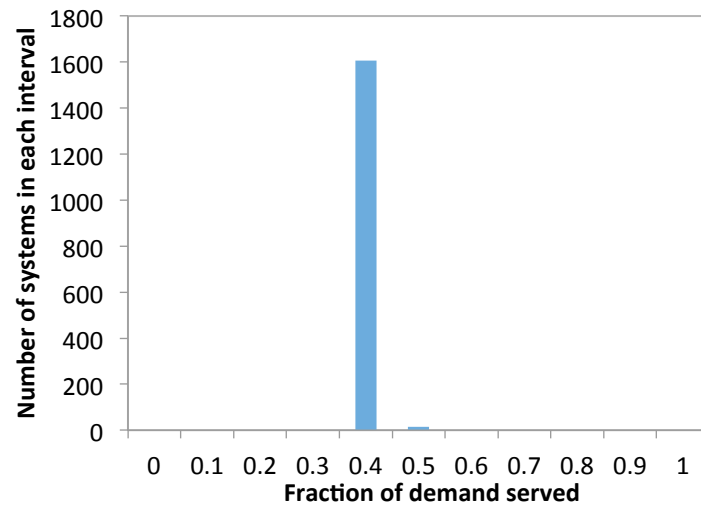


Figure 5-13: Fraction of demand served by microgrids

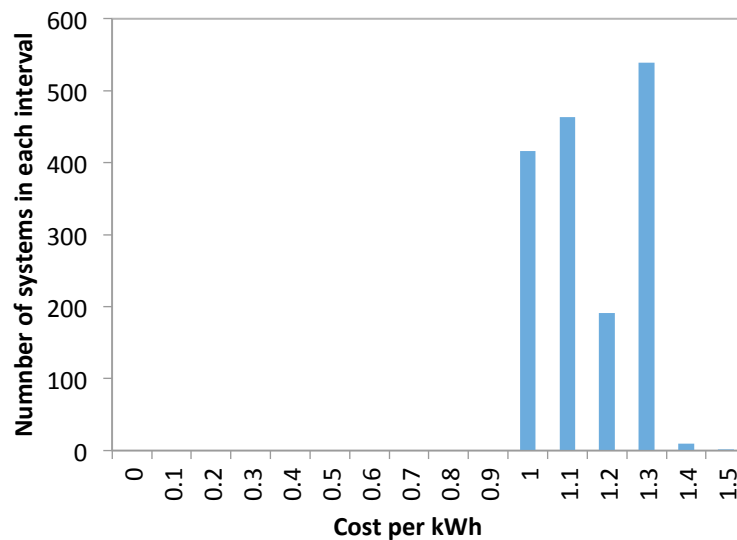


Figure 5-14: Electricity cost per kWh for microgrids

Table 5-6 shows the comparison between the above scenario and the base case scenario 1. When the diesel price is varied, it affects the cost of off-grid solution, as diesel generator is considered one of the generation assets for microgrid. When the diesel price is high, as expected, the cost of electricity from microgrid is high (\$0.62/kWh vs. \$1.03/kWh). Diesel generator mainly serves as a generation asset to strengthen the reliability of the system. When diesel is expensive, the reliability of the microgrid goes down, since now most of the microgrid is only solar PV-battery supported.

Table 5-6: Summary of cost and performance results by system for scenarios varying the price of diesel

	Scenario 1 (\$1/L)	Scenario 4 (\$2/L)
Grid Extension		
Annual Financial Cost per Household	\$88.84	\$85.36
CNSE per Household	\$40.92	\$40.90
Percentage of Demand Served	93.8%	93.8%
Cost per kWh	\$0.46	\$0.44

Microgrids		
Number of Households per Microgrid	26	7
Annual Financial Cost per Household	\$108.80	\$72.49
CNSE per Household	\$15.15	\$102.76
Percentage of Demand Served	89.9%	33.8%
Cost per kWh	\$0.62	\$1.03
Isolated Home Systems		
Annual Financial Cost per Household	\$127.19	\$127.19
CNSE per Household	\$102.75	\$102.75
Percentage of Demand Served	33.9%	33.9%
Cost per kWh	\$1.80	\$1.80
Total Annual Financial Cost	\$4,633,388	\$3,515,843
Total Annual Financial & NSE Cost	\$5,315,759	\$5,934,611

Scenario 5 (grid reliability 93.75%; solar only off-grid systems)

This scenario, where off-grid systems are restricted to solar only options, is intended to represent a renewable energy policy emphasis. The results are somewhat similar to the high diesel case in Scenario 4. In this scenario, the largest percentage of households, 75%, were assigned to grid extension, while 25% were assigned to microgrids, and less than 0.01% of isolated customers were assigned to a SAS.

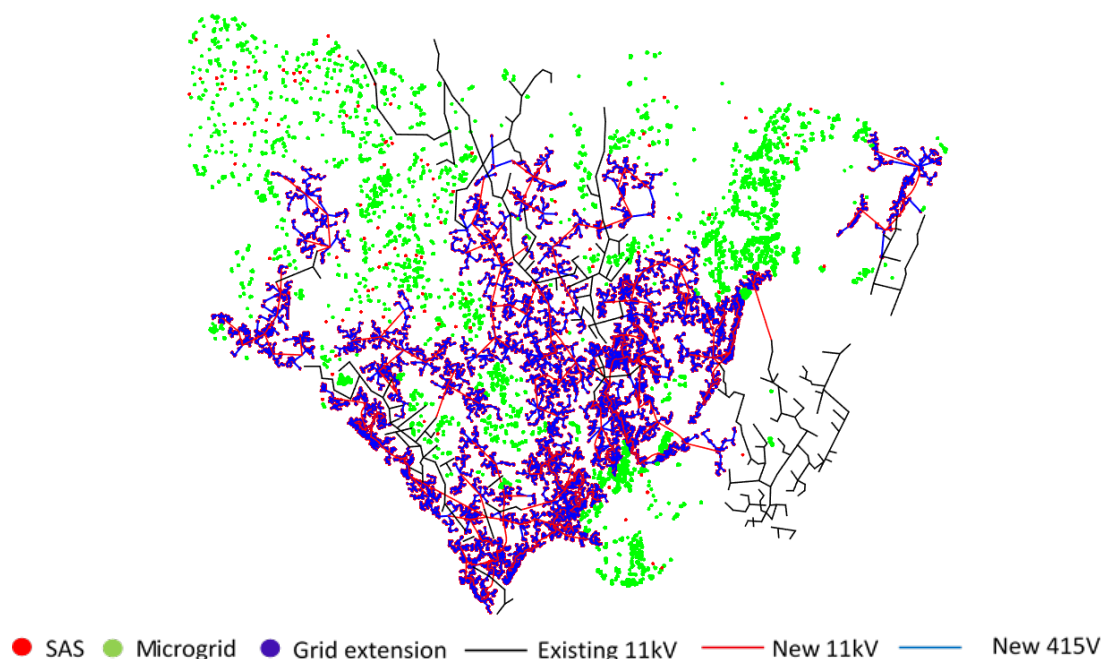


Figure 5-15: REM result for Scenario 4 showing different electrification solutions

The average annual financial cost of grid connection per household connected to the grid was \$82.87 while the average cost per kWh of demand served with the grid was \$0.42.

There were a total of 1,383 microgrids, ranging in size from 2 to 98 households connected to a single system, although the average was around 8 households per microgrid. The average financial annual cost of a microgrid connection per household was \$68.70 and the average

cost per kWh of demand served with a microgrid was \$1.01. The microgrids served about 33% of the demand for each household, on average.

For the 99 isolated households, the average annual financial cost per household was \$127.54 for a system consisting of a 250W PV array and a 0.48 kWh battery bank in each household. The average cost per kWh of demand served was \$1.80. The individual system served 34% of demand per household.

Table 5-7: Results summary for Scenario 5

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	10,476	99	32,180	42,755
Fraction of Customers	0.25	0.00	0.75	1
Financial Cost Per Customer (\$/yr)	68.70	127.54	82.87	79.50
Non-served Energy Cost Per Customer (\$/yr)	105.41	103.38	40.96	56.90
Total Financial Cost (\$/yr)	719,708	12,627	2,666,704	3,399,039
Total Financial and Non-served Energy Cost (\$/yr)	1,824,031	22,861	3,984,765	5,831,657

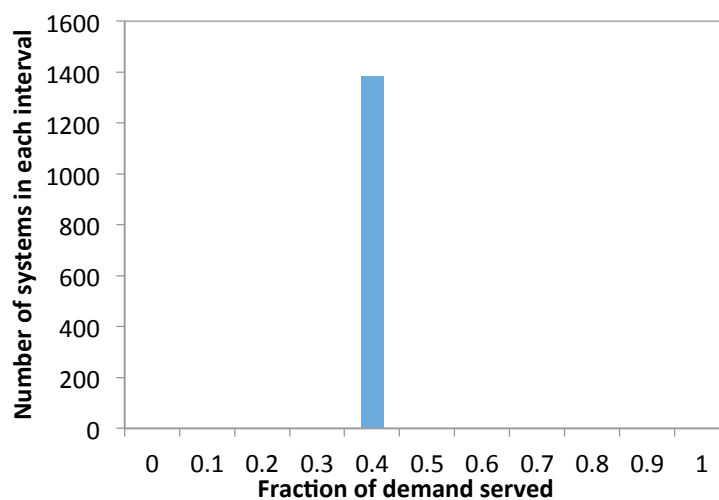


Figure 5-16: Fraction of demand served by microgrids

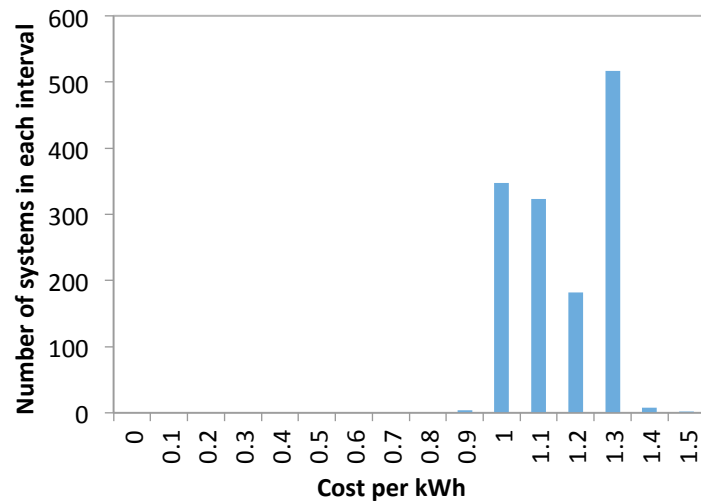


Figure 5-17: Electricity cost per kWh for microgrids

Table 5-8 shows the comparison between the above scenario and the base case (scenario 1). Scenario 5 looks at just solar as an option for off-grid solutions, looking at all renewable option. The diesel price is kept prohibitively high (\$10/liter). As with the previous run with high diesel cost, the least cost solution for electrification for majority of the population is through grid extension, and wherever off-grid solution do make sense, they are also very expensive compared to Scenario 1.

Table 5-8: Summary of cost and performance results by system when off-grid systems are constrained to be solar only

	Scenario 1	Scenario 5 (solar only off-grid systems)
Grid Extension		
Annual Financial Cost per Household	\$88.84	\$82.87
CNSE per Household	\$40.92	\$40.96
Percentage of Demand Served	93.8%	93.8%
Cost per kWh	\$0.46	\$0.42
Microgrids		
Number of Households per Microgrid	26	8
Annual Financial Cost per Household	\$108.80	\$68.70
CNSE per Household	\$15.15	\$105.41
Percentage of Demand Served	89.9%	32.7%
Cost per kWh	\$0.62	\$1.01
Isolated Home Systems		
Annual Financial Cost per Household	\$127.19	\$127.54
CNSE per Household	\$102.75	\$102.75
Percentage of Demand Served	33.9%	33.9%
Cost per kWh	\$1.80	\$1.80
Total Annual Financial Cost	\$4,633,388	\$3,490,887
Total Annual Financial & NSE Cost	\$5,315,759	\$5,904,160

Scenario 6 (grid reliability 93.75%; diesel price \$1/liter; ~5x Demand)

The following two scenarios show what change in the solutions would result if household demand grew at a faster rate than assumed in the base case. In this scenario, the largest percentage of households, 94%, was assigned to microgrids, and 6% of isolated customers were assigned to a SAS. No households were assigned to grid extension.

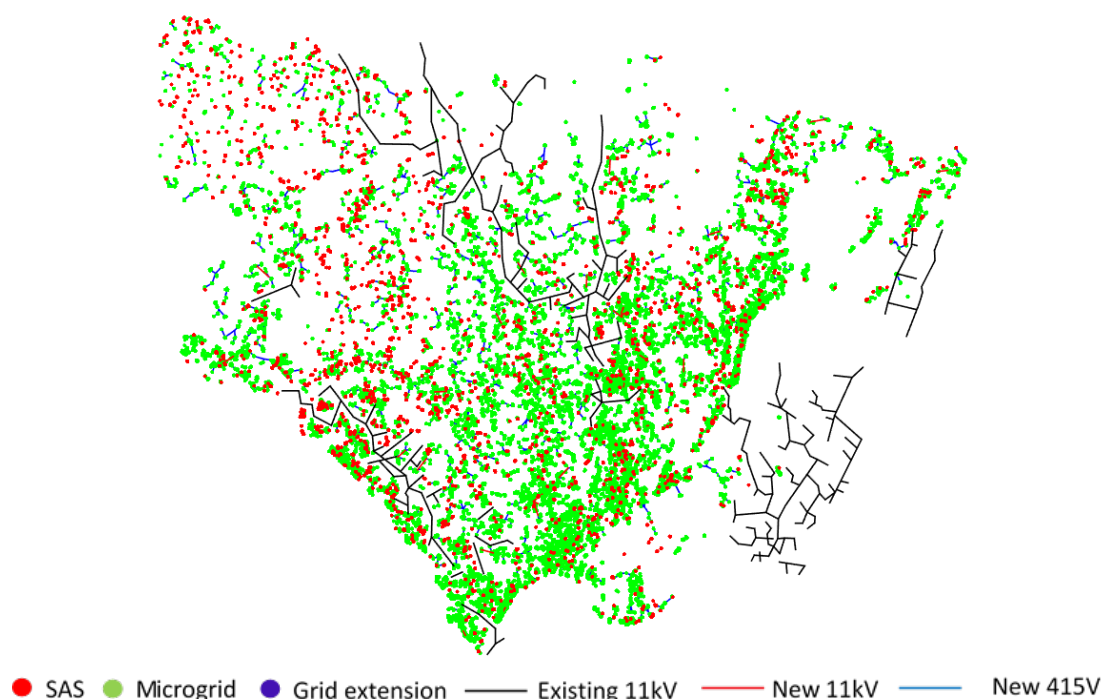


Figure 5-18: REM result for Scenario 6 showing different electrification solutions

There were a total of 1,812 microgrids, ranging in size from 2 to 289 households connected to a single system, although the average was around 22 households per microgrid. The average financial annual cost of a microgrid connection per household was \$576.93 and the average cost per kWh of demand served with a microgrid was \$0.46. The microgrids served about 98% of the demand for each household, on average.

For the 2,632 isolated households, the average annual financial cost per household was \$645.34 for a system consisting of a 1 kW PV array and a 6.12 kWh battery bank in each household. The average cost per kWh of demand served was \$0.76. The individual system served 66% of demand per household.

Table 5-9: Results summary for Scenario 6

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	40,123	2,632	0	42,755
Fraction of Customers	0.94	0.06	0	1
Financial Cost Per Customer (\$/yr)	576.93	645.34	N/A	581.14
Non-served Energy Cost Per Customer (\$/yr)	18.87	333.39	N/A	38.23

Total Financial Cost (\$/yr)	23,148,154	1,698,537	0	24,846,691
Total Financial and Non-served Energy Cost (\$/yr)	23,905,097	2,576,027	0	26,481,124

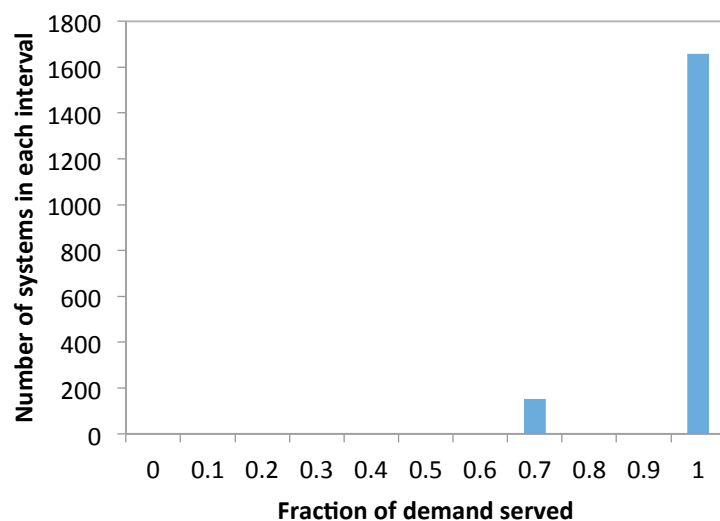


Figure 5-19: Fraction of demand served by microgrids

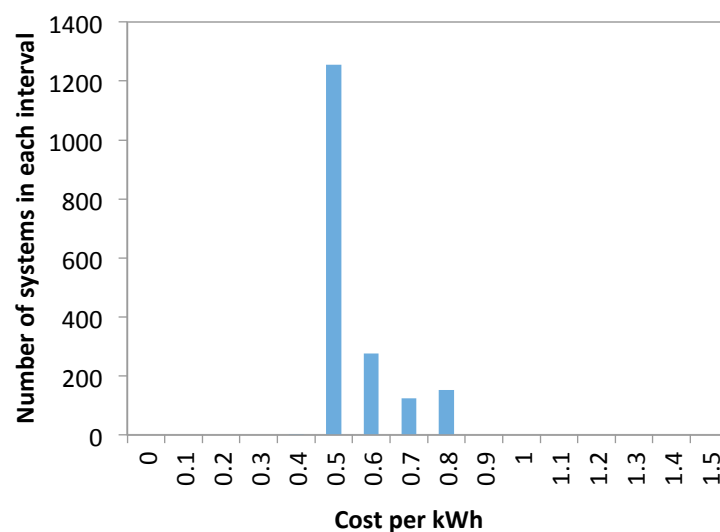


Figure 5-20: Electricity cost per kWh for microgrids

Scenario 7 (grid reliability 93.75%; diesel price \$1/liter; ~10x Demand)

In this scenario, the largest percentage of households, almost all households were assigned to microgrids, with only 3 isolated customers assigned to a SAS. No households were assigned to grid extension.

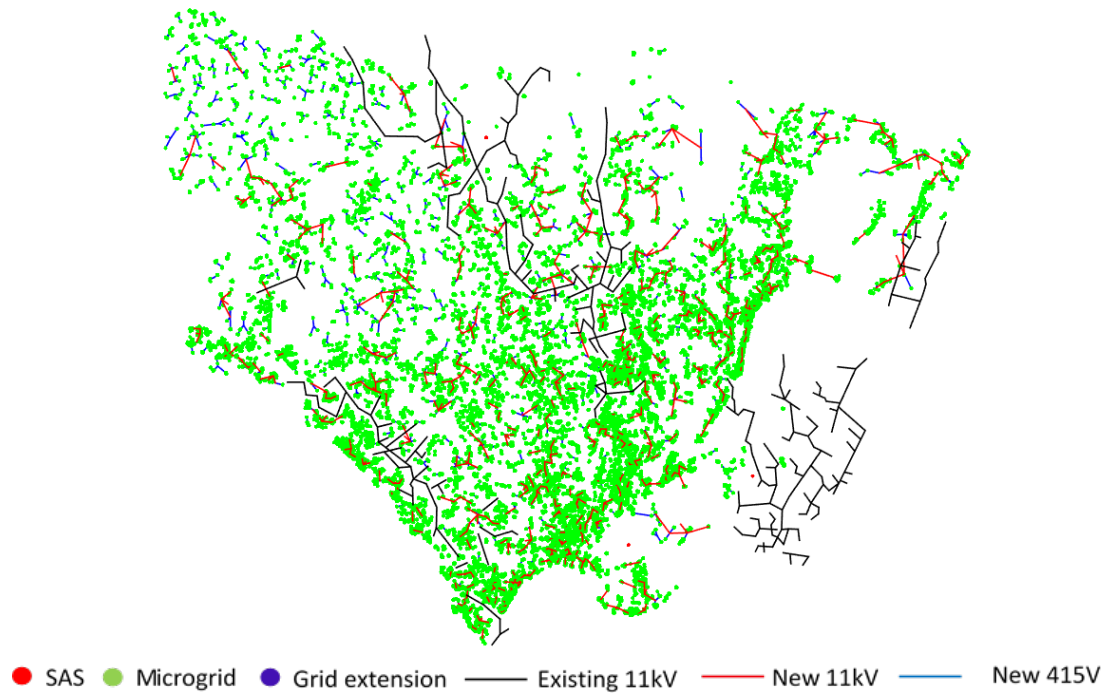


Figure 5-21: REM result for Scenario 7 showing different electrification solutions

There were a total of 2,355 microgrids, ranging in size from 2 to 266 households connected to a single system, although the average was around 18 households per microgrid. The average financial annual cost of a microgrid connection per household was \$2,430.24 and the average cost per kWh of demand served with a microgrid was \$0.36. The microgrids served about 99% of the demand for each household, on average.

For the 3 isolated households, the average annual financial cost per household was \$3,556.06 for a system consisting of a 2.833 kW PV array, a 4.16 kWh battery bank, and a 1.67 kW diesel generator in each household. The average cost per kWh of demand served was \$0.53. The individual system also served about 99% of demand per household.

Table 5-10: Results summary for Scenario 7

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	42,752	3	0	42,755
Fraction of Customers	1	0.00	0	1
Financial Cost Per Customer (\$/yr)	2,430.24	3,556.06	N/A	2430.32
Non-served Energy Cost Per Customer (\$/yr)	41.38	45.78	N/A	41.38
Total Financial Cost (\$/yr)	103,897,528	10,668	0	103,908,196
Total Financial and Non-served Energy Cost (\$/yr)	105,666,782	10,805	0	105,677,597

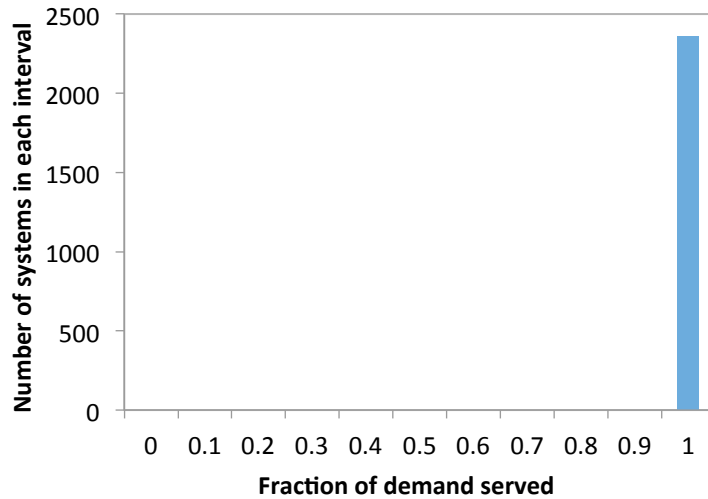


Figure 5-22: Fraction of demand served by microgrids

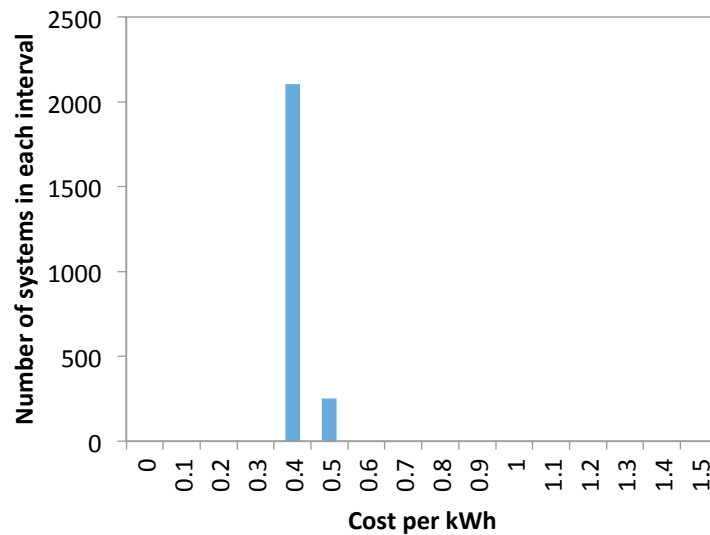


Figure 5-23: Electricity cost per kWh for microgrids

Table 5-11 shows the comparison between the above scenarios and the base case (scenario 1). The interesting result for this analysis show that even with ~94% grid reliability, if the demand is large, without strengthening the current grid (i.e. making it more reliable), the lesser-cost solution for electrification is microgrid. As the demand increases, the overall cost per energy from microgrid also decreases, since the assets are used to full capacity with better utilization rate, and the overall cost of the system is distributed among large load or energy demand.

Table 5-11: Summary of cost and performance results by system when demand is increased

	Scenario 1	Scenario 6 (higher demand)	Scenario 7 (much higher demand)
Grid Extension			
Annual Financial Cost per Household	\$88.84	N/A	N/A
CNSE per Household	\$40.92	N/A	N/A

Percentage of Demand Served	93.8%	N/A	N/A
Cost per kWh	\$0.46	N/A	N/A
Microgrids			
Number of Households per Microgrid	26	22	18
Annual Financial Cost per Household	\$108.80	\$576.93	\$2,430.24
CNSE per Household	\$15.15	\$18.87	\$41.38
Percentage of Demand Served	89.9%	98.4%	99.2%
Cost per kWh	\$0.62	\$0.46	\$0.36
Isolated Home Systems			
Annual Financial Cost per Household	\$127.19	\$645.34	\$3,556.06
CNSE per Household	\$102.75	\$333.39	\$45.78
Percentage of Demand Served	33.9%	66.2%	99.1%
Cost per kWh	\$1.80	\$0.76	\$0.53
Total Annual Financial Cost	\$4,633,388	\$24,846,691	\$103,908,196
Total Annual Financial & NSE Cost	\$5,315,759	\$26,481,124	\$105,677,597

Scenario 8 (grid reliability 100%; diesel price \$1/liter; ~5x Demand)

Since REM currently does not include the failure and maintenance rates for off-grid systems, Scenario 8 was created to determine the effect of not including this data on the results, particularly in light of the high costs for providing electricity (part of which are due to servicing higher demand) seen in Scenarios 6 and 7. In this scenario, the largest percentage of households, 75%, were assigned to grid extension, while 24% were assigned to microgrids and slightly less than 1% of isolated customers were assigned to a SAS.

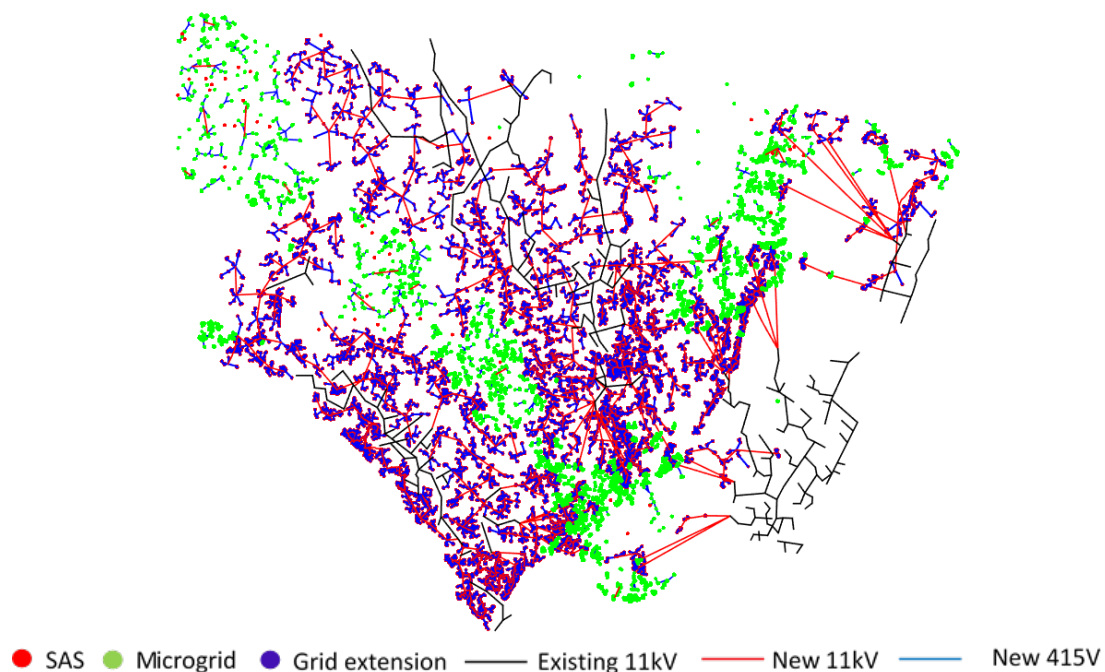


Figure 5-24: REM result for Scenario 8 showing different electrification solutions

The average annual financial cost of grid connection per household connected to the grid was \$363.54 while the average cost per kWh of demand served with the grid was \$0.28.

There were a total of 378 microgrids, ranging in size from 2 to 173 households connected to a single system, although the average was around 28 households per microgrid. The average financial annual cost of a microgrid connection per household was \$576.55 and the average cost per kWh of demand served with a microgrid was \$0.45. The microgrids served about 99% of the demand for each household, on average.

For the 43 isolated households, the average annual financial cost per household was \$648.75 for a system consisting of a 1 kW PV array and a 6.24 kWh battery bank in each household. The average cost per kWh of demand served was \$332.31. The individual system served 66% of demand per household.

Table 5-12: Results summary for Scenario 8

	Microgrids	Isolated Systems	Grid Extensions	All
Number of Customers	10,441	43	32,271	42,755
Fraction of Customers	0.24	0.01	0.75	1
Financial Cost Per Customer (\$/yr)	576.55	648.75	363.54	415.84
Non-served Energy Cost Per Customer (\$/yr)	15.74	332.31	0	4.18
Total Financial Cost (\$/yr)	6,019,803	27,896	11,731,695	17,779,395
Total Financial and Non-served Energy Cost (\$/yr)	6,184,107	42,186	11,731,695	17,957,988

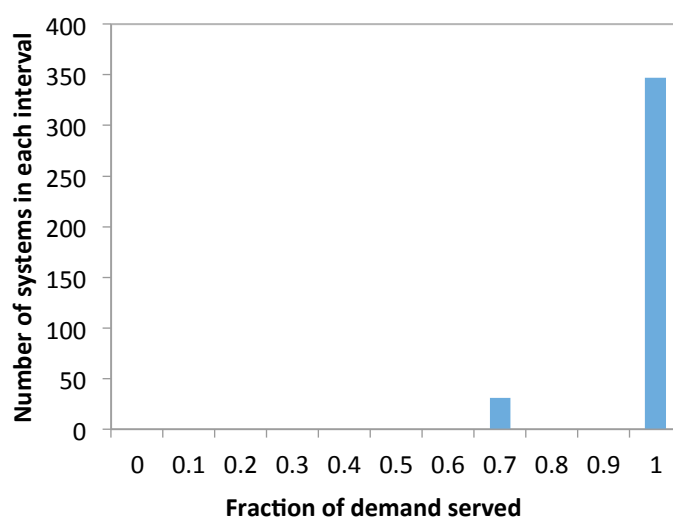


Figure 5-25: Fraction of demand served by microgrids

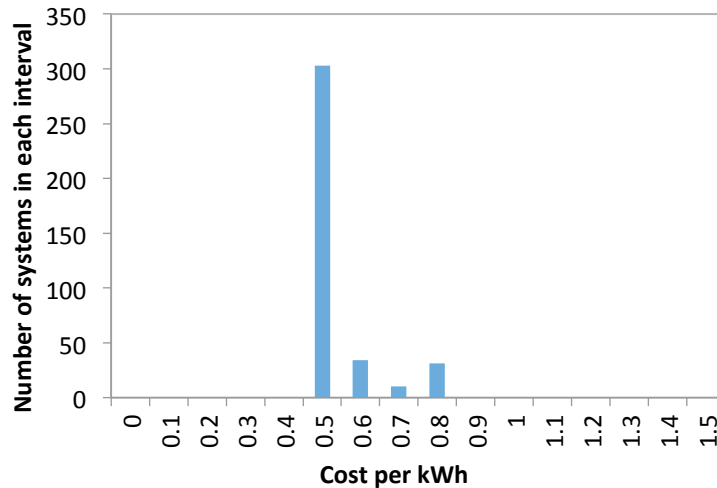


Figure 5-26: Electricity cost per kWh for microgrids

Table 5-4 shows the comparison between the above scenario (with 100% grid reliability) and the higher demand scenario when grid reliability is set to 93.75% (Scenario 6). This comparison shows the importance of the condition of grid. With better grid reliability, when the demand increases, grid extension is the optimum solution for the majority of the households.

Table 5-13: Summary of cost and performance results by system varying grid reliability when demand is increased (higher demand scenarios)

	Scenario 6 (93.75%)	Scenario 8 (100%)
Grid Extension		
Annual Financial Cost per Household	N/A	\$363.54
CNSE per Household	N/A	\$0.00
Percentage of Demand Served	N/A	100%
Cost per kWh	N/A	\$0.28
Microgrids		
Number of Households per Microgrid	22	28
Annual Financial Cost per Household	\$576.93	\$576.55
CNSE per Household	\$18.87	\$15.74
Percentage of Demand Served	98.4%	98.7%
Cost per kWh	\$0.46	\$0.45
Isolated Home Systems		
Annual Financial Cost per Household	\$645.34	\$648.75
CNSE per Household	\$333.39	\$332.31
Percentage of Demand Served	66.2%	66.2%
Cost per kWh	\$0.76	\$0.76
Total Annual Financial Cost	\$24,846,691	\$17,779,395
Total Annual Financial & NSE Cost	\$26,481,124	\$17,957,988

Limitations

The numbers presented here are preliminary and based on data collection and assumptions from parallel work on cases in Vaishali, India (Ellman, 2015; Borofsky, 2015) where data from Kilifi was lacking. The demand profile has been estimated based on various studies and from the group's experiences of working in India and Rwanda. Proper estimation of the demand for Kenya would be needed to get more accurate results. Similarly, we have used a more generic pricing structure for generation assets, and network assets based on our work in India, and that needs to be matched by the numbers available for Kenya. As such, they are meaningful primarily for relative case comparison purposes only. Future planning exercises would require more accurate data specific to the Kenyan context.

5.2 Cooking and Heating

RCM as a tool has the aim of estimating the cost of increasing access to modern cooking fuels while minimizing environmental impact, which, in this first instance, is approximated by particulate matter emissions. **Figures 5-10** shows the current distribution of households using the different technologies for Kilifi County. Since the census data includes only the primary fuel used for cooking, households using wood and charcoal as their predominant fuel were divided evenly among the 6 wood stoves and 2 charcoal stoves respectively.

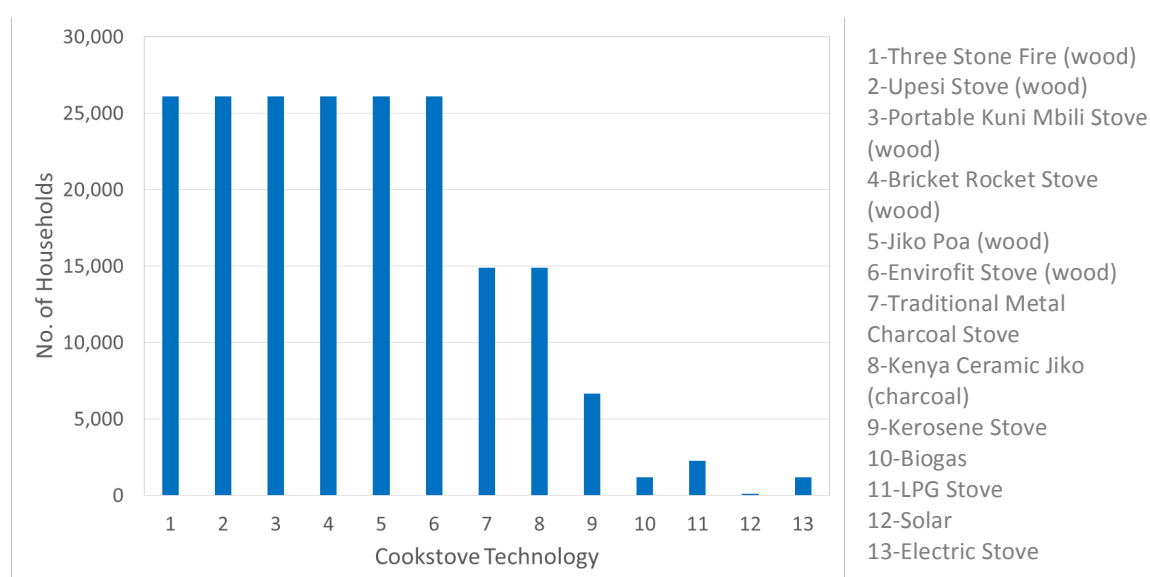


Figure 5-10: Current distribution of households using various cook stove technologies in Kilifi County

The summary of results is presented in **Tables 5-14**. These reference scenarios assume that households spend 5% of their income on their energy needs (Pueyo, 2015), and upfront stove costs are also annualized. Using the 5% affordability threshold, the results suggest that of the 67% of households currently using wood fuel in Kilifi County, 24% could afford to transition to the advanced fuel category without any subsidy. A similar implication holds for the almost 30% currently using charcoal and kerosene (transition fuels). These conclusions are drawn from the fact that with 0 government budget, the solution could achieve nearly 70% pollution reduction level. The budget needed to move to more advanced cookstoves can come from within the households, if the assumption of 5% income spending towards cooking energy need holds true. RCM results show transitions that happen where most of the households

using primitive fuel can afford to buy advanced cookstoves on their own. Similarly, household using transition fuels can also move to the advanced cookstoves bracket by spending 5% of their household income. The output from RCM also shows total fuel resources used for different category of cookstoves i.e. total wood, kerosene, LPG, electricity etc. Within RCM, wood is the only biomass considered, and there is no distinction between other biomass such as animal dung, twigs etc.

Table 5-14: Summary of RCM results for Kilifi County

PM Reduction Target	Gov't Budget (million KES)	Proportion of Households			Resources Used					
		<i>Primitive Fuels</i>	<i>Transition Fuels</i>	<i>Advanced Fuels</i>	<i>Wood (tonnes)</i>	<i>Charcoal (tonnes)</i>	<i>Kerosene (tonnes)</i>	<i>LPG (tonnes)</i>	<i>Biogas (tonnes)</i>	<i>Electricity (MWh)</i>
0%	0	43%	0%	57%	54,648	0	0	0	0	143,726
10%	0	43%	0%	57%	54,648	0	0	0	0	143,726
20%	0	43%	0%	57%	54,648	0	0	0	0	143,726
30%	0	43%	0%	57%	54,648	0	0	0	0	143,726
40%	0	43%	0%	57%	54,648	0	0	0	0	143,726
50%	0	43%	0%	57%	54,648	0	0	0	0	143,726
60%	0	43%	0%	57%	54,648	0	0	0	0	143,726
70%	43.718	43%	0%	57%	54,648	0	0	0	0	143,726
80%	125.6	33%	0%	67%	42,020	0	0	0	0	168,720
90%	294.432	17%	0%	83%	21,010	0	0	0	0	210,302

As a variation, two other thresholds of affordability (in terms of the percentage of household expenditure consumers are assumed to spend on fuel) are also modeled (see **Table 5-15**). Using 0% of household expenditure has the same effect as showing total financial cost (regardless of who bears it). This scenario shows a steadily increasing trend in terms of the budget required with higher pollution reduction targets (see **Table 5-15**). The 10% threshold supports the observation stated above that there are households that could afford to use more modern fuels, but have not chosen to do so.

Table 5-15: Comparison of RCM budget results for Kilifi County when the affordability threshold is changed

PM Reduction Target	Gov't Budget (million KES)		
	0% expend.	5% expend.	10% expend.
0%	958.355	0	0
10%	958.355	0	0
20%	962.265	0	0
30%	969.064	0	0
40%	976.649	0	0
50%	1,052.692	0	0
60%	1,302.534	0	0
70%	1,575.911	43.718	0
80%	1,906.703	125.600	9.732
90%	2,248.591	294.432	32.146

Table 5-16a and **Table 5-16b** shows different fuel consumption percentage for different affordability thresholds, and the quantity of various cooking resources for those respective affordability thresholds. With the households providing 0% for any transition, most of them still use primitive fuels i.e. wood, and very few have advance fuels. With higher PM reduction target, the government budget increases, and the percentage of households using advanced fuels also increases.

Table 5-16a: Comparison of RCM results for Kilifi County showing the proportion of households using various fuels when the affordability threshold is changed

PM Reduction Target	Primitive Fuels			Transition Fuels			Advanced Fuels		
	0% expend.	5% expend.	10% expend.	0% expend.	5% expend.	10% expend.	0% expend.	5% expend.	10% expend.
0%	79%	43%	22%	19%	0%	0%	2%	57%	78%
10%	79%	43%	22%	19%	0%	0%	2%	57%	78%
20%	79%	43%	22%	19%	0%	0%	2%	57%	78%
30%	79%	43%	22%	19%	0%	0%	2%	57%	78%
40%	79%	43%	22%	19%	0%	0%	2%	57%	78%
50%	69%	43%	22%	29%	0%	0%	2%	57%	78%
60%	37%	43%	22%	61%	0%	0%	2%	57%	78%
70%	5%	43%	22%	92%	0%	0%	2%	57%	78%
80%	0%	33%	22%	69%	0%	0%	31%	67%	78%
90%	0%	17%	17%	34%	0%	0%	66%	83%	83%

Table 5-16b: Comparison of RCM results for Kilifi County showing the quantity of each type of resource used when the affordability threshold is changed

PM Reduction Target	Wood (tonnes)			Kerosene (tonnes)			Electricity (MWh)		
	0% expend.	5% expend.	10% expend.	0% expend.	5% expend.	10% expend.	0% expend.	5% expend.	10% expend.
0%	100,000	54,649	28,358	5,952	0	0	6,024	143,726	195,759
10%	100,000	54,649	28,358	5,952	0	0	6,024	143,726	195,759
20%	100,000	54,649	28,358	5,952	0	0	6,024	143,726	195,759
30%	100,000	54,649	28,358	5,952	0	0	6,024	143,726	195,759
40%	100,000	54,649	28,358	5,952	0	0	6,024	143,726	195,759
50%	87,351	54,649	28,358	9,059	0	0	6,024	143,726	195,759
60%	46,947	54,649	28,358	18,986	0	0	6,024	143,726	195,759
70%	6,543	54,649	28,358	28,913	0	0	6,024	143,726	195,759
80%	0	42,020	28,358	21,508	0	0	78,625	168,720	195,759
90%	0	21,010	21,010	10,754	0	0	165,255	210,302	210,302

Another dynamic pattern explored here is the impact of upfront costs on the solutions the model provides. As has been previously discussed, upfront costs can pose a significant hurdle to the adoption of improved technologies. Most low-income users typically favor fuels like charcoal and kerosene because they can be bought in small quantities (on a per mass or volume basis), which they can afford. The results suggest that, in seeking to reduce indoor air pollution, more households would use transition fuels than modern fuels (see **Table 5-17a** and **Table 5-17b**) because of the financial burden that the initial purchase of stoves for advanced fuels would impose: the price of an electric stove, for example, is on average more than 70 times more expensive than the charcoal Kenya Ceramic Jiko—KES 35,000 compared to KES 400 respectively. The quantity of each type of resource used for each threshold is also provided in **Table 5-17c** for comparison purposes.

Finally, changes in demand are also modeled. Increasing or decreasing household energy demand for cooking fuels by 25% also increases or decreases (respectively) the amount of resources used, but does not change the relative distribution of households using each category of fuel.

Table 5-17a: Comparison of RCM budget results for Kilifi County when initial stove costs are annualized (*FCAnn*) vs. when they are not (*FCnotAnn*)

PM Reduction Target	Gov't Budget	
	<i>FCnotAnn</i>	<i>FCAnn</i>
0%	0	0
10%	0	0
20%	0	0
30%	0	0

40%	0	0
50%	149.429	0
60%	201.933	0
70%	462.900	43.718
80%	1,741.536	125.600
90%	3,554.309	294.432

Table 5-17b: Comparison of RCM results for Kilifi County showing the proportion of households using various fuels when initial stove costs is annualized (*FCAnn*) vs. when they are not (*FCnotAnn*)

PM Reduction Target	Primitive Fuels		Transition Fuels		Advanced Fuels	
	<i>FCnotAnn</i>	<i>FCAnn</i>	<i>FCnotAnn</i>	<i>FCAnn</i>	<i>FCnotAnn</i>	<i>FCAnn</i>
10%	43%	43%	55%	0%	2%	57%
20%	43%	43%	55%	0%	2%	57%
30%	43%	43%	55%	0%	2%	57%
40%	43%	43%	55%	0%	2%	57%
50%	43%	43%	55%	0%	2%	57%
60%	37%	43%	61%	0%	2%	57%
70%	5%	43%	92%	0%	2%	57%
80%	0%	33%	69%	0%	31%	67%
90%	0%	17%	34%	0%	66%	83%

Table 5-17c: Comparison of RCM results for Kilifi County showing the quantity of each type of resource used when initial stove costs are annualized (*FCAnn*) vs. when they are not (*FCnotAnn*)

PM Reduction Target	Wood (tonnes)		Kerosene (tonnes)		Electricity (MWh)	
	<i>FCnotAnn</i>	<i>FCAnn</i>	<i>FCnotAnn</i>	<i>FCAnn</i>	<i>FCnotAnn</i>	<i>FCAnn</i>
0%	54,649	54,649	3,782	0	6,024	143,726
10%	54,649	54,649	3,782	0	6,024	143,726
20%	54,649	54,649	3,782	0	6,024	143,726
30%	54,649	54,649	3,782	0	6,024	143,726
40%	54,649	54,649	4,365	0	6,024	143,726
50%	54,649	54,649	17,094	0	6,024	143,726
60%	46,947	54,649	18,986	0	6,024	143,726
70%	6,543	54,649	28,913	0	6,024	143,726
80%	0	42,020	21,508	0	78,625	168,720
90%	0	21,010	10,754	0	165,255	210,302

Limitations

There are several factors that have not been incorporated into the version of RCM presented in this thesis:

- Other environmental impact (carbon dioxide emissions)
- Safety (fire risk, burns)

- Conformity¹⁹
- (In) convenience²⁰
- Adequacy²¹

This analysis includes only fuel cost, fuel and stove conversion efficiency, and particulate matter emissions (as a proxy for health impacts). The overarching framework allows for determining the overall technical performance of the primary cook stove while taking into account the conformity, convenience, and adequacy (CCA) attributes which touch upon the issues of maintenance, convenience, and social and cultural fit. A recent study (Hanna et al., 2012) aimed at evaluating how improved stoves perform in real-world conditions over long time horizons showed that “improved cook stoves in India did not reduce smoke exposure, improve health, or reduce fuel usage of recipients because *they were not used regularly* and recipients *did not invest to maintain them properly*” [emphasis added]. Such factors require more careful thought into how to model them mathematically (and even then, the question arises as to whether mathematical representation is the right approach). Other attributes such as the availability and affordability of both stoves and fuels should also be integrated into calculations (requiring detailed knowledge of the supply chain for any technology option), and would ground-truthing to ensure data accuracy.

A related note concerns that of resource availability more generally. There are constraints on biomass and solar availability incorporated in the model, but sources of LPG, kerosene, biogas, and electricity are assumed to be unlimited. While this may hold true when considering a relatively small study area compared to entire countries or other larger regions, it can represent an unrealistic option if the results from RCM suggest that a household (or group of households) should be using LPG or electricity, for example, but there are no LPG depots in the area and the household(s) do not have access to the grid.

More broadly, RCM represents an ideal situation: what fuels households should be using in order to minimize the effect of PM emissions. The reality that presents itself, however, is much more complex. As noted in Schlag & Zuzarte (2008), there are several market barriers to clean cooking fuel transition: traditional fuels are typically much cheaper and more widely available than modern alternatives; stoves for use with the modern alternatives have very high upfront costs; the infrastructure for the distribution of fuels like LPG is underdeveloped and even lacking in some regions; there is poor informational exchange between producers and customers (consumers may not be aware of the options available to them, manufacturers have limited data on household energy use patterns which makes it difficult to determine the commercial viability of alternatives); and various social and cultural issues (as touched on

¹⁹ To account for whether the household uses components of improved stoves such as chimneys and hoods—meant to provide the added value over traditional options—in the manner required, as well as other factors like regular stove cleaning and maintenance.

²⁰ In this thesis, an estimated numerical factor making solar cookers a costly alternative is implemented as there is evidence showing that most consumers prefer to cook in the mornings and evenings as opposed to during the day when the solar resource is highest. Other factors such as fuel accessibility and stove preparation, however, are not included.

²¹ To account for fuel stacking, i.e., that the primary stove meets majority of the household’s cooking needs.

above) that “reinforce” the reliance on traditional fuels. As such, a more holistic approach is needed to achieve universal access to modern fuels. Some successful pilot projects on the dissemination of improved cookstoves, for example, have involved more comprehensive approaches that associated the change of the stoves to a social program that included the beneficiaries collecting material to prepare the fuels (such as briquettes) to be used for these stoves (see, for example, Bailis et al., 2009; EnDev, 2012; Ooko, 2013; Shankar et al., 2015).

6. Conclusion

In the context of the energy access challenge that emerging economies face, this project has described and developed a comprehensive methodology that is proposed for the assessment of the appropriate modes of electrification and heating and cooking for specific countries or regions using a technology toolkit consisting of two models:

1. REM provides a means to perform objective quantitative assessments about the most convenient (least cost) way to provide electricity service, comparing together the three major electrification modes. The model allows the evaluation of the merit of: (a) extending the existing grid; (b) building isolated grids with local generation (microgrids); and (c) installing isolated stand-alone systems (SAS) for each target building. It is an innovative tool that can be used by planners at the national or regional scale to do electrification planning with rural access in mind. REM can also be used by utilities and small-scale energy entrepreneurs to access electricity market, and scout locations where grid-extension or off-grid solutions make viable economic sense.
2. RCM as a tool has the aim of estimating the cost of increasing access to modern cooking fuels while minimizing environmental impact, which, in this current implementation, is approximated by particulate matter emissions.

The analytical strategy presented here is based on a case study of Kilifi County, but is also intended to be generalizable for other administrative regions where access to electricity and modern fuels is a planning priority. The larger goal of this project, through the case study approach, has been to provide a proof of concept for the decision support tools being developed that could be used in the pursuit of universal energy access.

6.1 Key Findings

Electrification

Three sets of analyses were conducted in REM using eight scenarios for comparison purposes. The scenarios differed in the values assigned to grid reliability, the price of diesel and the total demand. Scenario 1 represents the baseline scenario, or our best estimate of the current state of the electric grid in Kaloleni, and as such, was used for comparison in all three sets of analyses. In the first set of comparisons, the grid reliability was varied to show how it affected the final electrification solution for non-electrified customers. If the grid is not very reliable, REM connected most of the new customers to microgrid, which would provide cheaper solution than connecting to grid. When the grid was 100% reliable, in Kaloleni's case, most of the new customers would be grid connected. Similarly, in the second set of comparisons, diesel prices were varied to show its effect on final electrification solution. With high diesel prices, the cost of microgrid increases, as it is one of the generation components for a microgrid. With very high diesel prices, we wanted to limit the generation asset of a microgrid to purely PV. In this case, the microgrid is expensive in many cases compared to grid, and grid extension becomes a viable solution for most new connections. In the last set of analysis, we looked at different demand growth. Many times with larger demand, but low reliable grid, off-grid solutions are least-cost solution. However, with 100%

grid reliability again grid extension becomes the most viable solution. The purpose of these runs was to show the ability and the potential of REM as a powerful tool that can help analyze electrification planning for different types of scenarios. The main results were as follows:

1. Varying reliability of the grid

These scenarios showed the importance of grid reliability in the determination of a solution for electrification. The lower the quality of the grid, the higher the proportion of off-grid systems used to meet customers' needs. This can be attributed to high cost of non-served energy for grid connection. As the grid gets more reliable, for the majority of the customer grid extension becomes the least cost option for electrification.

2. Varying diesel price

It was demonstrated that the cost of diesel has large implications on the economics of off-grid systems, particularly in the current implementation of REM where the microgrid and stand-alone systems consist of some combination of a PV array, a battery bank, and a diesel generator. Diesel generator provides high reliability to off-grid systems. Currently, breakdowns in diesel generators have not been considered, thus they provide highly reliable service. As a part of core algorithm development, operation and maintenance of diesel generator is being considered in more detail. As the diesel price increases, the overall cost of having microgrid also increases, making grid extension more cost effective. At the same time, the microgrid solutions that are provided for few customers are of lower reliability as they compose mostly of solar PV and battery combination.

3. Varying electricity demand

In this working paper, we also demonstrated utilization of REM to analyze different demand scenarios. As demand grows, the electrification solution for a particular community or a region could vary. It is important to identify the exact energy demand for which electrification planning is being conducted. With different runs from REM, one can see how the solution space varies as demand changes. This could provide important insight for planners who want to design the system with various demand growth projection in mind. One of the things that were shown from our analysis in this working paper is the connection between various demand profiles and the condition of grid. For higher demand than the base case scenario, with lower reliable grid, microgrids became dominant solution. Whereas if the grid conditions were good (~100% reliable), grid extension was a viable solution for most of those customers.

Cooking

The main conclusions drawn from RCM were as follows:

1. Using 5% affordability thresholds for household expenditure on fuel, the results suggest that of the 67% of households currently using wood fuel in Kilifi County, 24% could afford to transition to the advanced fuel category without any subsidy. A

similar implication holds for the almost 30% currently using charcoal and kerosene (transition fuels). Using a 10% threshold supported the observation stated above that there are households that could afford to use more modern fuels, but have not chosen to do so.

2. Upfront costs can pose a significant hurdle to the adoption of improved technologies. In seeking to reduce indoor air pollution, the results suggest that more households would use transition fuels than modern fuels because of the financial burden that the initial purchase of stoves for advanced fuels would impose.
3. Increasing or decreasing the assumed level of demand for cooking fuels also increased or decreased (respectively) the amount of resources used, but did not change the relative distribution of households using each category of fuel.

6.2 Future Work

What follows is a brief commentary on recommendations for future work in improving the methodology proposed herein.

REM

As demonstrated in this work, REM is a powerful tool that can be used to provide rapid assessment of the cost effectiveness of various electrification modes over large regions. The numbers presented here, however, are preliminary and based on data collection and assumptions from parallel work on cases in Vaishali, India, where data from Kilifi was lacking. As such, they are meaningful primarily for relative case comparison purposes only. Future planning exercises would require more accurate data specific to the Kenyan context.

Specific changes that would improve the accuracy of the results obtained include:

- The inclusion of costs for upstream reinforcements of generation and the transmission and distribution network to account for the increase in the number and demand level of households connected to the grid. There are different models that could be used in conjunction with REM to take into account these upstream reinforcement costs.
- The incorporation of outage time (for failures & maintenance) of off-grid systems.
- The incorporation of the design of high voltage lines for cost comparison to more realistically account for the presence of rather large microgrids in solutions (something not previously encountered in previous iterations of REM).

More broadly, REM is a static model that considers decisions to be made at a point in the future. Considering multi-step investment decisions in the network (or other electrification systems) and the year-to-year changes in parameters such as demand would also improve the accuracy of the results. Along with the technical and least-cost solution provided by REM, the team at MIT is also building a financial modeling aspect as a post-processing part of REM, where the overall cost as well as annual financial cost could be broken down into more appropriate parameters such as subsidy structures, tariff structures, annual return on investment rates etc. The Financial analysis could help utilities and regulators decided on subsidy policies or tariff rates for rural electrification. At the same time, entrepreneurs could also utilize the tool to figure out appropriate business models for microgrid operation.

RCM

RCM is a good approach as a first approximation, but the problem of access to modern fuels for cooking and heating is much more complex. Several market barriers to clean cooking fuel transition exist: traditional fuels are typically much cheaper and more widely available than modern alternatives; stoves for use with the modern alternatives have very high upfront costs; the infrastructure for the distribution of fuels like LPG is underdeveloped and even lacking in some regions; there is poor informational exchange between producers and customers; and various social and cultural preferences “reinforce” the reliance on traditional fuels. As such, a more holistic approach is needed to achieve universal access to modern fuels.

Specific changes that would improve the accuracy of the results obtained include:

- A better understanding of the supply chain for both fuels and stoves in the region in order to incorporate more accurate information on their availability and affordability.
- The incorporation of resource availability constraints for LPG, kerosene, and electricity (particularly when analyzing larger study areas).

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