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COMPARISON OF FINANCING MECHANISMS IN FACILITATING RURAL ELECTRIFICATION IN TANZANIA -USING AGENT BASED MODELING APPROACH

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ABSTRACT
Modern energy access is a prerequisite for social and economic prosperity. While the pace of central grid expansion may leave remote and rural areas underserved, using local Distributed Generation (DG) such as PV and micro-hydro can bring significant potential for decentralised electrification. The evolution of successful electrification is dynamic and adaptive, dependent on how the local and neighboring economies react. We evaluate such dynamics to assess how technology choice (grid expansion vs decentralised options) and financing (micro-loans vs. capital subsidies) can be leveraged to maximize the electrification potentials such as electrification rate as well as village income level. We develop the Integrated Rural Electrification Planning (IREP) tool, an agent-based model (ABM), to observe the organic evolution of electrification networks considering high-resolution geographic and economic features applied in rural Tanzania. We find that, combining capital subsidies and microloans brings synergy and electrification potentials will be maximized if microloan product is tailored to varying local needs, such as a year of electrification, occupation type as well as seasonal income stream.

Keyword: *Rural electrification planning, Agent-based modeling, Productive uses of electricity, Modern energy access*

1. INTRODUCTION

Conventional central grid expansion plans are mostly based on political and economic decisions that may leave remote and rural areas underserved (Innovation Energie Developpement 2014)(Ahlborg & Hammar 2014)(World Bank 2008) (Urmee et al. 2009). For some rural areas this creates the risk of an energy poverty trap, as energy is vital for economic prosperity and improving quality of life. As part of the “Sustainable Energy for All” (SE4ALL), the United Nations includes the goal of “access to affordable and reliable, sustainable and modern energy for all” in the Sustainable Development Goals (SDGs) (Anon 2015a). In response, developing countries including Kenya, Tanzania, Uganda, Bangladesh and India have prioritized investments for electrification in rural and remote areas (Moner-Girona et al. 2016).

This paper employs an agent-based modeling tool to investigate how to efficiently use this electrification budget. By leveraging the dynamics and interplay between electrification and local economic development in rural areas (e.g. cost reductions, income growth, etc.), financially viable systems can be created that “seed” further deployments as demand increases over time.

1.1 Problem Identification

The rural electrification projects in developing countries have been mostly implemented using donor aids, without much consideration on financial viability of the off-grid projects and needs or wants of a community. Therefore, often the rural electrification projects showed poor revenue stream, leaving the infrastructure obsolete for years and proving no visible impacts in the village after electrification. This myopic planning merely for increasing a number of connections did not improve the well-being of rural people nor did result in efficient use of local resources.

Many survey and interview results indicate that poor financial viability is the result of undersized or oversized systems and unreliable services. These systems therefore end up losing end users’ trust in paying for services and failing to attract investors’ interests further.

In order to better estimate demand of users and implement a successful energy system, a planner should consider comprehensive aspects including socio-economic context of a village (willingness to pay), payment schemes, technological maturity, economic policies and regulation and financing instruments that can fill the financing gap for rural electrification.

1.2 Limitations in Existing Approaches for Rural Electrification Planning

Modeling for planning rural electrification takes different approaches of varying complexity. Techno-economic assessments are widely used to determine system design parameters that will match villages' demand with supply (Pandey 2002). Future electricity demand is estimated by using income levels as a proxy and different system configurations are evaluated to minimize the Levelized Cost of Energy (LCOE). This approach was applied on a large scale by Szabo et al to analyze different technology options for Sub Saharan Africa (SSA) and identify the least cost portfolio (Szabó et al. 2011).

In practice, case studies of actual projects report mismatched system sizing as a key reason for project failure and poor financial viability. The forecasted demand did not match the reality of end user behaviors after the system was installed. To address this gap, Fishbein et al through the Energy Sector Management Assistance Program (ESMAP) recommend deriving future demand pattern and income growth rate using the correlation between productive use of electricity and consumption as an alternative (Fishbein et al. 2003)(Cabraal et al. 2005) (Fishbein et al. 2003) (Abdullah & Markandya 2012).

In an effort to capture the inherent complexity and interdependencies in energy system planning, simulation methods such as System Dynamics (SD), Agent Based Modeling (ABM) (Bollinger 2013), Monte-Carlo simulation, decision theory, game theory and multi-criteria techniques were also applied (Jordan & Emerson 2013). Steel used SD to model interactions between consumer decision making on the infrastructure type and performance of electricity infrastructure in Kenya (Steel 2008). Her model captures the behavioral pattern of end users in response to the poor quality of the existing central grid system and their frustration from waiting for the central grid extension.

In spite of the fact that the model points out the key reinforcing loop between financial and technical performance of a system by comprehensive causal loop diagrams (Daniel Schnitzer, Deepa Shinde Lounsbury, Juan Pablo Carvallo & Jay Apt 2014), important aspects of power system operation such as generation price or unmet demand were not considered in the investment decision. Jordan (Jordan & Emerson 2013) extended this framework further by combining SD with Mixed Integer Programming (MIP) optimization in the context of the Tanzanian electricity sector to validate an endogenous demand growth formulation in comparison to historical demand behavior. The model optimized central power system operations composed of thermal, solar and hydro units, however, off-grid solutions were not considered.

1.3 Methodology

In this work, agent based modeling (ABM) is chosen among other available methodologies due to several reasons. First, ABM is the most relevant approach to account for localities that are critical in the design of off-grid energy systems. For instance, in using ABM, we can easily incorporate different geographic nature, such as location of watersheds and calculate LCOE of microhydro based on these localities. In addition, it is easy to model context specific behavioural effects such as Word of Mouth (WoM) effect in deploying off-grid systems.

The platform used for ABM is a multi-method simulation tool called "Anylogic". It can complement ABM with system dynamics, optimization, and GIS feature simultaneously. This overcomes limitations of so-called black box approaches by showing "how" that scenario was achieved.

2. MODEL DESCRIPTION

2.1 Model Perspective

Integrated Rural Electrification Planning Model (IREP-M) is a decision support tool for rural electrification in Tanzania. Having 20 rural villages in Tanzania as "agents" the model firstly identifies the electrification option that suits the needs of a village by asking:

What is the most attractive [reliable, affordable and socially acceptable] electrification option to implement, considering the geographic, socio-economic characteristics of a village?

Each village has four alternative electrification options: grid extension, microhydrdo, hybrid PV-diesel microgrid and solar home systems (SHS). A decision metric for choosing the most attractive electrification option is composed of three indexes-1) quality of service, 2) affordability and 3) social acceptance. All three indicators dictate the estimated satisfaction level on energy services based on their needs and wants. The agent in the model act as a local project developer who aims to choose not only the least cost option but also an option that can provide reliable energy service with sufficient social acceptance from end users. The project developer in this context aims to maximize economic situation of a village through energy services, not only focusing on the numbers of installations. Hence, a second question we attempt to answer is:

Which financing mechanism is more effective in maximizing income of a village?

We compare and analyse the impact of two different financing mechanisms -1) capital subsidies and 2) microcredits- in facilitating rural electrification in Tanzania. By simulating it over decades, the model allows us to estimate the impacts on a village. To measure impacts, three key performance indicators are tracked-1) electrification rate, 2) average income level, and 3) ratio of decentralised systems over total number of villages.

2.2 Model Structure and Parameters

The model is composed of two layers: 1) the GIS environment (country level where agents are all located and 2) agents (village level).

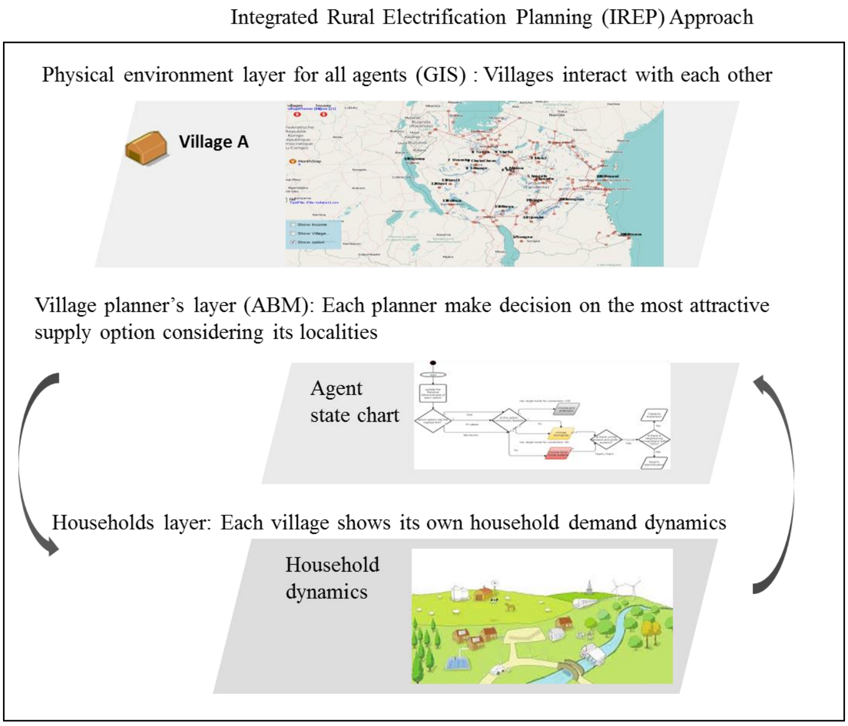


Figure 1. Integrated Rural Electrification Planning (IREP) model framework

In the GIS environment (a country level), some major geographic information such as location of watershed and existing grid network are presented. In the beginning of the simulation, user interface allows users to adjust values for exogenous inputs like total rural electrification budget and technology differentiated subsidy levels-in this work, we reflect the reality of Tanzanian electricity sector. Tanzania has allocated USD 415 million annually to electrify 30% of the total population by 2022, of which only 4% is dedicated to off-grid technologies, while 80% is planned for grid development. Rural Energy Agency (REA) has recently offered incentives to renewable based microgrids. Small power producers (SPP) with a capacity less than 1MW, very small power producers (VSPP) with less than 100kW and suppliers in rural areas receive a licensing fee exemption for projects. SPPs who produce power using PV are offered a fixed rate tariff of 0.24 $/kWh (Kirubi et al. 2009) and 0.10$/kWh for hydro. SPP owners are allowed to set their own cost-reflective tariff to ensure a reasonable rate of return.

In the agent level, each village has two types of agents created to describe supply and demand dynamics. First "**Village**" type agent determines the supply option. Using geographic features and economic characteristics of a village, the Village agent goes through a decision algorithm and chooses the most the affordable, reliable and socially acceptable electrification option. More details of decision algorithm are elaborated in Section2.3.1. In reality, this decision can be taken by a local project developer or village cooperative leader who prioritizes utility of a community over economic utility of the government. The parameters of Village type agent are described below.

Secondly "**Households**" type agent determines the demand dynamics. Using assumptions based on household survey results on end user behaviors, desired consumption of a household is estimated as a sum of residential consumption and productive consumption according to the occupation type and income level (i.e. high, middle and low) (Bhatia & Angelou 2015). Yet, actual consumption level is restricted to the amount a household can afford.

2.3 Model Process

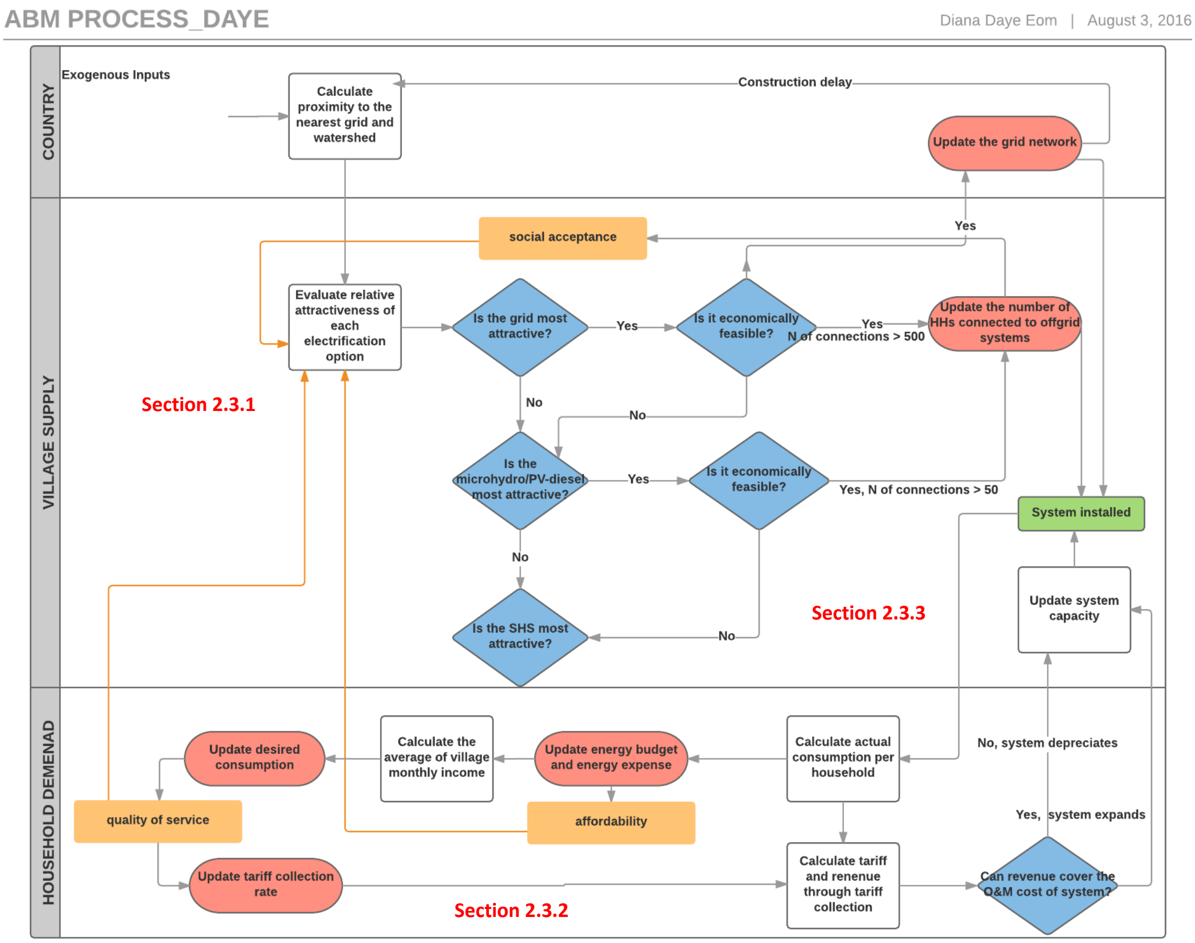


Figure 2. Model process overview

2.3.1 Decide the Most Attractive Electrification Option

The decision algorithm in Figure 4 shows that Relative Attractiveness (RA) is a decision metric to initiate the process. Agents or village project developers choose the option with the highest RA at a point in time for a given budget. The attractiveness (a) of each option is a composite of three attributes: level of affordability (A), quality of energy services (QoS), and social acceptance (SA). The sensitivity to each metric is adaptive according to the village estimates. Prior to each decision, changes in spatial information such as "proximity to the nearest energy system" are updated. Therefore, the most attractive option for a village is continuously re-evaluated. The Relative Attractiveness shows the village's readiness on each option and a village electrification network emerges as the aggregation of all decisions from a village level. The formula of a decision metric for attractiveness is as following:

$$a = \exp(E_a + E_{QoS} + E_{sa}) \quad (1)$$

$$E_x = \frac{X}{X_r} \times Sensitivity_{attribute} \quad (2)$$

$E_a: Effect\ of\ Affordability$
$E_{QoS}: Effect\ of\ QoS$
$E_{ca}: Effect\ of\ Social\ acceptance$

$Sensitivity_{attribute}$: $Customer' sensitivity\ to\ each\ attribute$
$(affordability, quality\ of\ service\ and\ social\ acceptance)$
X_r: $Reference\ value\ that\ denotes\ community's\ initial\ expectation\ or\ desired\ state$

Affordability: Affordability is the ratio between electricity expense and energy budget. Energy budget is proxied by Income Energy Ratio (IER) which refers to the portion of monthly income spent for energy use in rural areas. There is a positive correlation between income growth and household expenditure on energy and we use the results from rural household budget survey in Kenya to parametrize IER (Abdullah & Markandya 2012).

$$energy\ budget = i * IER \qquad \because IER \quad = f(i) \tag{3}$$

$$A = \frac{energy\ budget}{t_e \times c_h} \tag{4}$$

$$t_e = LCOE_i * t_f - subsidy_i \tag{5}$$

$energy\ budget$: $willingness\ to\ pay\ (WTP)\ for\ energy\ as\ a\ portion\ of\ total\ income$ [$/month]

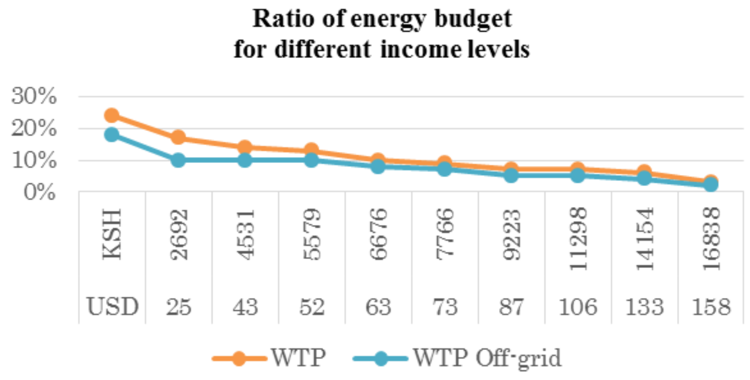


Figure 3. Income Energy Ratio as a function of monthly income level per household in Tanzania (Innovation Energie Developpement 2014)

i: $average\ income\ per\ households$ [$/month]
IER: $Income\ energy\ ratio$, dmnl
A: $affordability$, dmnl
t_e: $electricity\ tariff$ [$/kWh]
c_h: $actual\ consumption\ per\ HH$ [$/kWh]
$LCOE_i$: $LCOE\ of\ option\ i$ [$/kWh]
$(i = 0: central\ grid, i = 1: hybrid\ diesel\ PV\ microgrid,\ \ i = 3: microhydro, i = 4: SHS)$
t_f: $tariff\ factor\ (subsidy, tax\ etc)$, dmnl
$subsidy_i$: Technology specific off-FiT for PV and hydro in Tanzania

Affordability increases when tariff (t_e) is reduced, actual consumption (c_h) is small or energy budget ($energy\ budget$) is increased due to income growth. Over the simulation, tariff can be reduced due to several reasons: 1) firstly due to swarming, and 2) secondly due to proximity effect and lastly due to3) capital subsidy provided for a specific technology. The swarming increases the number of households connected and so the cost burden can be spread out. The latter refers to the grid arrival in the neighboring village which reduces the proximity to the nearest system, and thus reduction in transmission cost. Technological learning or import tax exemption of capital can be other factors driving cost reduction but it is not accounted here. It is likely to have the positive correlation between income and consumption-the more income you earn the more electricity budget you have.

Quality of service: The quality of service measures two related indicators: sufficiency and availability (technology specific) (Daniel Schnitzer, Deepa Shinde Lounsbury, Juan Pablo Carvallo & Jay Apt 2014). This indicator describes an important link (refer to the bottom link in Figure 2) between financial viability and technical performance of energy system, showing poor performance can lead to the technical failure of the system whereas good performance can expand the customer base.

Social Acceptance: Lastly, the value of social acceptance is initialized as uniform distribution using validated survey results from the literature (Nassen et al. 2002)–users prefer grid connection as they perceive the option as unlimited supply. The lack of knowledge on potential benefits of decentralized systems is also a reason for this tendency. However, the social acceptance of villages to decentralized options increases as people interact with their neighbors (geographically close villages) who have positive experience on microgrids. This creates positive perception on decentralized systems. The effect is presented through simplified linear correlation as the ratio of decentralized system in a country rises (Jordan & Emerson 2013).

2.3.2 Electricity Consumption Drives Household Demand Dynamics

Once the electrification option is chosen, the "House" type agent drives the demand dynamics. Using the formulation of productive consumption and income gain as below, the level of demand endogenously changes.

Many studies found out that end user in rural areas show similar behavioural pattern across the country in terms of the amount of electricity they use for residential use, home appliances they desire as well as willing to pay for energy services. Residential use of electricity includes lighting, mobile phone charging, home appliances and entertainment. Figure 4shows the desired residential consumption level in relation to a household income level. The relationship is derived from the household assets survey by NBS, counting only electric appliances in rural households with different income levels (NBS 2014).

Productive uses are income-generating activities. While domestic use is universal and correlated to income level, productive use varies from occupation to occupation. Combining case studies and research on productive use, we collected a list of productive uses for each occupation type (Kirubi et al. 2009)(Abdullah & Markandya 2012)(NBS 2014) and generated distribution based on the figures (Figure 5). There is a wide consensus on the importance of productive use in expanding energy access as it enables users to accumulate assets and savings by increasing job opportunities and labour productivity. That said, distinguishing types of productive use or tracking income gained through productive use is quite challenging due to various external factors such as personal knowledge and experience, access to resources and willingness to invest in obtaining productivity-enhancing tools.

For instance, we estimate that a farmer with monthly income level 100$/month desires approximately 38kWh/month of residential consumption and 100kWh/month of productive consumption but affordable consumption being 100kWh/month. The actual consumption is estimated as the minimum value of affordable consumption and desired consumption, which is 100kWh/month multiplied by uncertainty factors. The formulation is as below:

$$desired\ residential\ consumption = f(income) \quad (6)$$
$$desired\ productive\ consumption = f(occupation) \quad (7)$$
$$desired\ consumption = desired\ residential\ consumption + desired\ productive\ consumption \quad (8)$$
$$Actual\ consumption = Uncertainty\ factor * min(affordable\ consumption, desired\ consumption) \quad (9)$$

$$Incomegain = Uncertainty\ factor * desired\ productive\ consumption \quad (10)$$

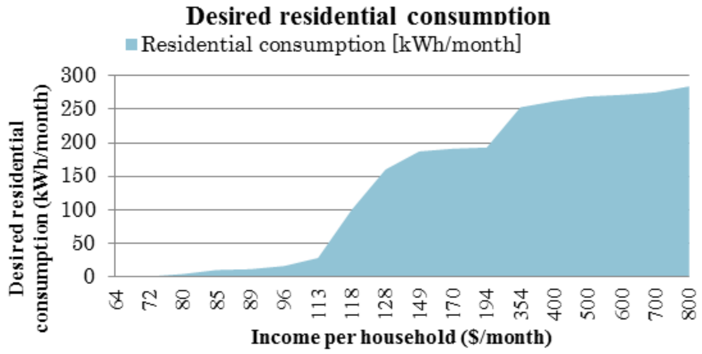
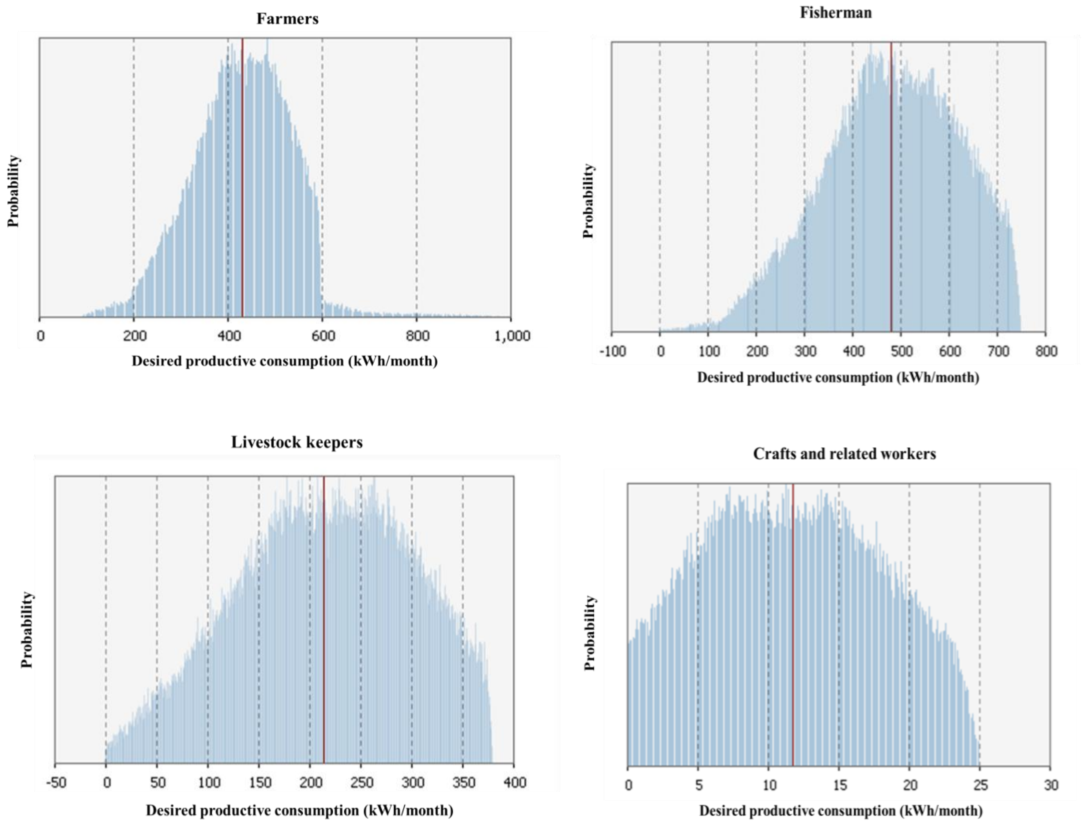


Figure 4. Desired residential consumption in relation to income levels



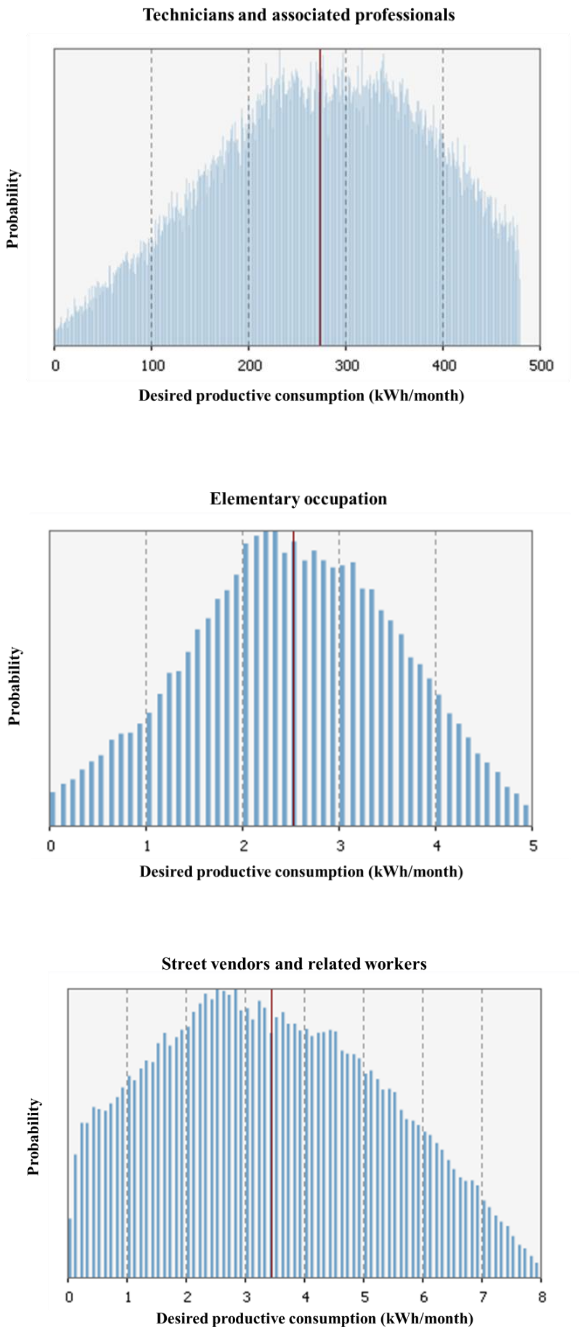


Figure 5. Distribution of desired productive consumption for each occupation type

Ultimately, we are interested in the amount of economic benefits that electricity can generate. In quantifying the monetary benefits, we use case studies from scholars in the field of productive use of electricity (Yadoo & Cruickshank 2012)(Practical Action 2013) (Barnes & Foley 2004) and multiply uncertainty factor, meaning that the income gain (10) from the same amount of productive use can vary, resulting a higher or lower income gain than expected, due to factors like existing infrastructure level of a village that may affect access to markets.

2.3.3 Demand Dynamics Affect Financial Viability of System

Once the energy system is installed and demand rises, maintaining financial viability of the system is important not only for an investor but also for users to access reliable services over a long time horizon (Jordan & Emerson, 2013). That means, the quality of system is only maintained if sales revenue is sufficient enough to cover the operation and maintenance (O&M) cost, otherwise the system is doomed to depreciate over the lifetime.

3. SCENARIO

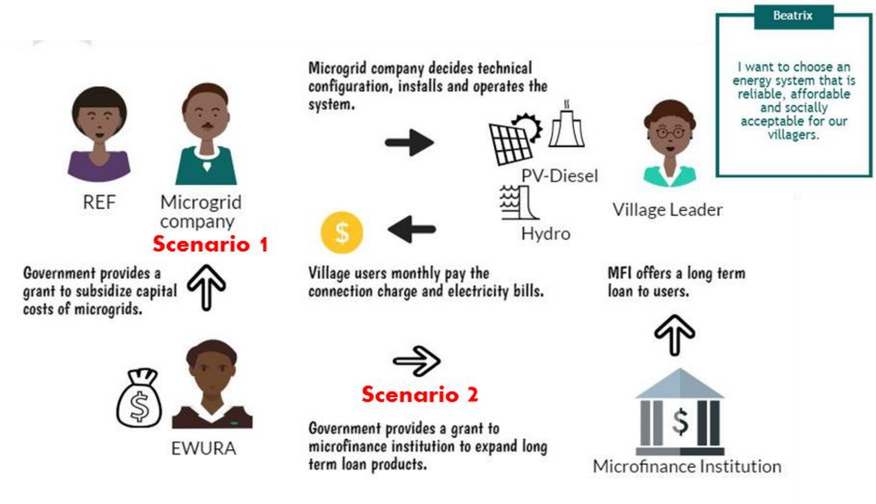


Figure 6. Scenario

Recent National Prospectus of Tanzania for electrification stresses the needs of having a ranking criteria of off-grid projects and thus project financing can be better targeted (Innovation Energie Developpement 2014). Therefore, we evaluate two different financial mechanisms to create an environment for financially viable systems: **Scenario I**) using REF to offer capital subsidies **and Scenario II**) using REF to offer microloan.

For capital subsidies, we apply the level of subsidy which Tanzania is currently having for PV and hydro. For microloans, we assume that government uses MFIs as intermediaries and offer lump sum loans to individual household. The microloan product we consider here is for purchasing productivity-enhancing tools including mills or grinders. The loan is accumulated as savings and users who are willing to invest purchase machinery of their interest.

We consider six different scenarios varying the ratio of rural electrification fund allocated to capital subsidies and microloans. All scenarios are compared based on three key performance indicators-1) electrification rate, 2) average income level, and 3) ratio of decentralised systems over total number of villages.

Parameters	Unit	Base	A	B	C	D	E
% of budget allocated to capital subsidies (only for off-grids)	%	100	80	60	40	20	0
% of budget allocated to microloans	%	0	20	40	60	80	100

Table 1. Scenario

4. RESULTS

In this section, we discuss the impacts and dynamics of most two common financing approaches for rural electrification, capital subsidies and microloan, over 20 years after the system installation.

4.1 Providing capital subsidies only is a temporary measure.

Providing capital subsidies for decentralised systems has been a common practice in developing countries to support its wider adoption. Yet the effectiveness in generating economic benefits in a long run was unclear. The simulation results show that, in comparison to microloans, providing capital subsidies is less effective in achieving higher electrification rate (a number of households and the amount of electricity provided) as well as higher average household income. This can be explained in a situation in which, microloan was provided even enough to cover the grid connection cost therefore resulted in the lowest decentralised system adoption rate (78.3%) among all scenarios (Figure 7). This implies that for rural users, affordability is the greatest constraint for a grid connection. However, the next lessons give another important caveat in designing rural electrification policies.

In both cases where 80% or 60% of fund was allocated to capital subsidies (Scenario A: 80 or Scenario B: 60), consumers rapidly increase the consumption level from the beginning, however, could not maintain their level of consumption after 11 years (Figure 8. Left figure). This is because households did not raise their income levels enough to be self-reliant (i.e. afford their demand levels without a capital subsidy) and were dependent on capital subsidies. Therefore, when rural electrification fund for capital subsidies were cut off, consumers could not pay for their electricity services, dropping down the consumption level to the extent they can afford. In short, providing capital subsidy can rapidly increase adoption rate of decentralised systems but without microloans, users cannot sustain electricity demand in a long term. Capital subsidies alone do not solve the problem, as it can merely exploit users' energy expense without giving them agency to generate income. In addition, such downstream subsidies can rather distort the learning potential in local economies if it is offered for too long.

On the other hand, when rural electrification fund was distributed almost evenly as capital subsidy (60%) and microloan (40%) the highest average village income was achieved. This would make sense if users who could not afford grid gained access by having decentralised option and gradually increased their potential to generate income through productive uses. The combined mechanisms seem to bring synergy in lowering high upfront cost barrier and increasing productive use of electricity.

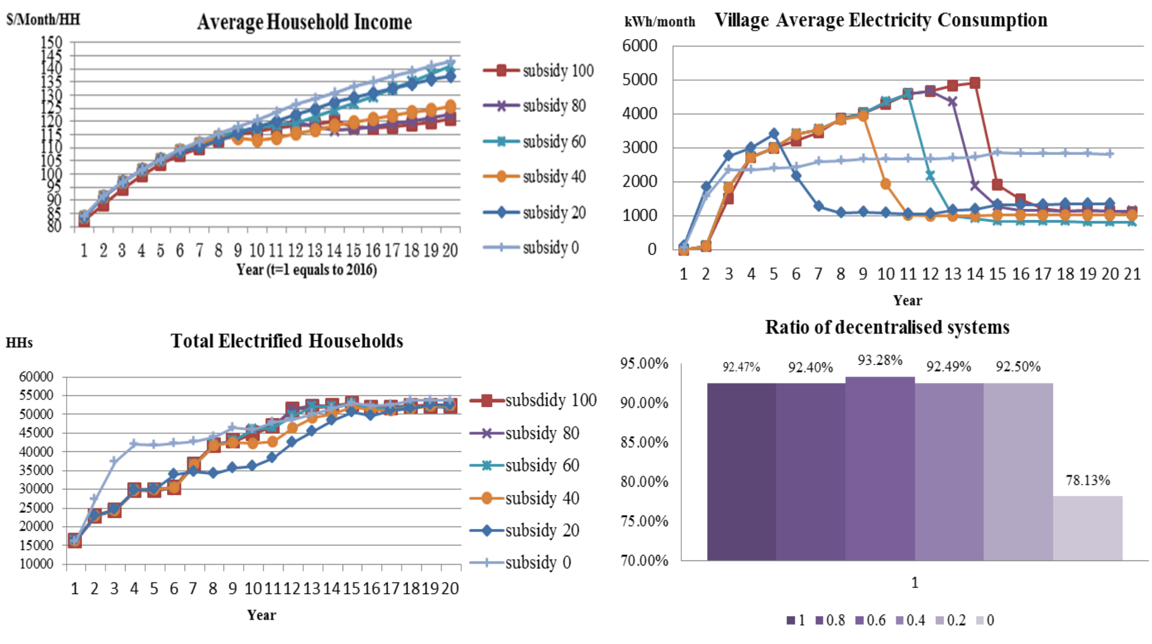


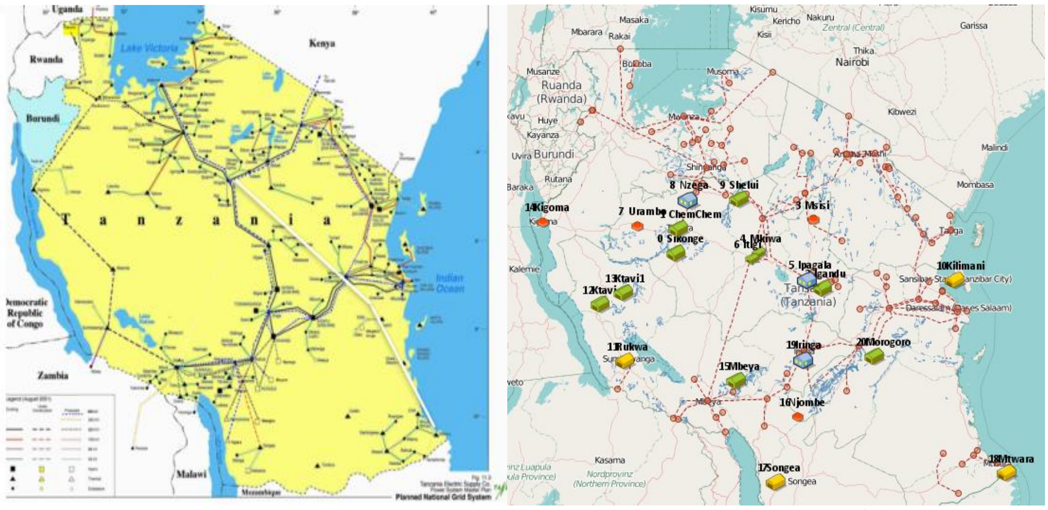
Figure 7. Results of Key Performance Indicators (Clockwise: Average household income level, village

average electricity consumption, total electrified households, ratio of decentralised systems)

4.2 Not only absolute amounts of rural electrification fund but also timing of provision and design of microloan product matters.

The core advantage of microloan is, due to liability issue, it motivates people to invest in various income generating activities or businesses by purchasing tools and therefore improving productivity. This means the needs for microloan can vary depending on the occupation type, size of enterprise, type of energy systems they own, desired electric appliances and energy services. In order to respond to these varying needs of customers, different microloan products can be designed for each occupation type-i.e. crop microloan, solar energy microloan, start-up microloan etc. Lending loans to a group with same occupation can also bring knowledge sharing experience among villagers. For the lowest income group, however, the story can be opposite-their income can be too small and irregular with seasonal variations. In this case, lending loan to a group of villagers with different occupations can offer opportunities to stabilize irregularities in cash flow and maximize the loan security.

Another potential strategy is to focus on the years of electrification. For instance, in the beginning of electrification, the consumption needs of a household will be rather modest whereas microloan becomes critical after the installation, when people start realizing the benefits of electricity and want to change their status quo which usually comes with years of delay. Therefore, in materializing microloan into productive use of electricity, years of electrification can provide more accurate picture of household's knowledge and desire in energy use.



* A green house represents a village where micro-hydro is the most attractive, a yellow house for PV-diesel hybrid, a red for solar home system and a lightened blue house for a grid extension. A simulation is only done for 20 villages, not for all villages in a country.

Figure 8. Electrification network in Tanzania (Left: Current, Right: Simulation Forecast by 2035 with Scenario (Subsidy 20, Microloan 80)

5. CONCLUSION

It is widely acknowledged that affordability is the most critical constraint for rural population to gain energy access. Capital subsidies and microloans are most commonly used financing mechanisms in rural electrification by lowering upfront cost barriers as well as providing access to capital. The simulation results provide two important insights for designing these financing schemes.

First, the model suggests that both capital subsidies and microloan should be provided to induce long lasting impacts of electrification as capital subsidy is considered for a short-term, as a stop gap measure only. What is more important to note is to maximize effectiveness of microloan through tailored design of microloan products. As an example, designing different microloan products in accordance with their years of electrification, lending microloan to a group of people with various occupations can stabilize the irregular cash flow of rural population. In conclusion, a tailored product that reflects borrower's cash flow and desired consumption level over a long-term horizon would maximize development impacts of electrification.

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