MODELLING TEMPORAL DIFFUSION OF PV MICROGENERATION SYSTEMS IN A RURAL DEVELOPING COMMUNITY

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ABSTRACT: An agent-based model (ABM) is developed in Netlogo as a tool for evaluating temporal diffusion of PV-based communal grids in a rural developing community. ABMs model individual entities within a complex system and the rules that govern the interactions of the entities within the system, to capture the overall effect of such interactions. Results show that given various choices, small PV mircogeneration systems would emerge as the prefered source of electrification for many households. Also, with increasing power demands, many household would prefer communal grids to the national utility grid. Furthermore, introduction of favourable government policies in the form of subsidies and mircocredit facilities, coupled with increasing social acceptance, would lead to increased PV installations and correspondingly to increased communal grid connections. Specifically, introduction of a subsidy of $0.15/kWh would result in an increase of 249% in communal grid connections. Increasing the sensing radius from 1 km to 2 km would result in an increase of 118% in communal grid connections.

Keywords: Communal Grids, PV Diffusion, Temporal, Agent-Based Model

1 INTRODUCTION

Development of electricity delivery infrastructures are path-dependent, meaning, each development decision and step affects subsequent steps, and the final outcome. Human actors are therefore the most important variables in any energy development plan as their decisions affect the way a system evolves. Proper policy-planning tools are therefore required to guide decision-makers on least cost rural electrification pathways. Many factors influence choices of technologies used in rural electrification, the main ones being availability of resources, cost, demand, social acceptance, and government policies. Different modelling tools and techniques have been applied in planning rural electrification paths in many countries. However, these often view this problem as a question of expansion of grid coverage through extensions of existing transmission and distribution networks and seldom address the unique and regionally-specific challenges presented by many developing nations. In most of sub-Saharan Africa for example, grid electricity is often unreliable, plagued with frequent blackouts, poor maintenance, and low quality of service. In these regions, expansions of the national grids often result in further strain on the systems and thus in further reduction in quality of services to those already grid-connected. Decentralized generation, transmission, and distribution of electricity based on locally available renewable energy resources offer potential solutions to low rural electrification rates in these communities.

Decentralized power generation systems are usually used as pre-grid electrification modulators, sensitizing and readying households for future grid connections, and are thus often abandoned once the latter arrives. This is more so with stand-alone systems which have limited power capacities. However, depending on local resources, capacities, designs and technologies used, communal grids could provide the final solutions to rural electrification in many developing nations and entrench green economies in the process. In fact, it is estimated that there will be almost 400TWh of installed green communal grid capacity by 2030, about 40% of new installed capacities towards universal electrification in developing nations [1]; communal grids offer many advantages over other options in that when compared to national grids, they are cheaper to put up, with shorter lead times, sized to match local demands, and are modifiable with increasing demands or changing technologies, while when compared to stand-alone systems, they offer access to higher power capacities and unlimited virtual storage, and could thus stimulate local microeconomic activities.

2 METHODOLOGY

In this work an agent-based model (ABM) is developed as a tool for evaluating temporal diffusion of PV-based communal grids in a rural sub-Saharan developing community to provide decision-makers with a user-friendly environment for PV-based rural electrification policy development, planning, and implementation. The model takes into account the complexities and limitations of solar electricity microgeneration technologies, decisions by human actors, geographical factors, and interaction between the three factors. ABMs seek to capture the overall macro-effects of different micro-decisions in a virtual world; they model individual entities within a complex system and the rules that govern the interactions of the entities within the system, to capture the overall effect of such interactions.

Survey data from a case study of Kendu Bay area of Kenya is used to inform the model. NetLogo was chosen for this work because it is user friendly, free, and easy to learn and modify, as is currently considered the best agent-based modelling software by researchers. The following agents are created in the model: a) a representation of the environment and the solar potential in it, b) the populations in it that require electricity, c) PV seeds that would use the environment to produce electricity, d) links to connected households to communal grids, and e) a central observer or stakeholder who determines the strategies and preferences for PV diffusions. Through these agents and the rules created for their interactions, the model sis used to simulate how step-decisions by human actors, based on prevailing local socio-economic factors and government policies, influence temporal diffusion of PV-based communal grids in a rural developing community.

Folowing the method of Opiyo et al. [2], a house without PV must first develop the idea to install PV given the following factors amongst others: a) cost, b) neighbourhood influence, c) government policies such as subsidies, and d) social pressure (advertisements). To calculate the idea to install PV (PVD), the above factors are combined as follows [9]

$$PVD = \sum_{i=1}^{n} W_i F_i \tag{1}$$

where n is the total numbers of factors, W_i is the weight associated with each factor F_i, and each F_i has a value between 0 and 1.

The idea to install PV returns true if

$$\frac{HPV_{SR}}{TH_{SR}} \times 100 > NT \tag{2}$$

where HPV_{SR} is the number of houses with PV within a given sensing radius (SR) or neighbourhood, TH_{SR} is the total number of houses within the same sensing radius, and NT is the neighbourhood threshold, minimum percentage of neighbours within the sensing radius who must have installed SHS for a household to develop the same.

If the idea to install PV returns true, cost comparison is done before a final decision is made. PV is installed if:

$$PVGC_{kwh} < AVC_{kwh} + S_{kwh} \tag{3}$$

where $PVGC_{kwh}$ is the PV generation cost per kWh, AVC_{kwh} is avoided cost per kWh, and S_{kwh} is subsidies per kWh.

Avoided cost per kWh, AVC_{kwh} is given by

$$AVC_{kwh} = NGC_{kwh} \tag{4}$$

where NGC_{kwh} is the prevailing national grid electricity cost per kWh.

PV generation cost per kWh ($PVGC_{kwh}$) is given by

$$PVGC_{kwh} = \frac{PVC_T}{(PVO \times PVL)} \tag{5}$$

where PVC_T is the total PV cost, PVO is the total PV output, and PVL is PV lifetime.
Total PV cost (PVC_T) is given by

$$PVC_T = (PVC_{m^2} - S_{m^2}) \times PV\varepsilon \times RS \times AF \tag{6}$$

where PVC_{m^2} is PV cost per m^2, S_{m^2} is subsidies per m^2, $PV\varepsilon$ is PV efficiency, RS is roof size available under PV Installation and ranges between 10m^2 and 50m^2, and AF is an accounting factor given by

$$AF = (1 + r)^{PVL} \tag{7}$$

where r is the interest rate and PVL is the PV lifetime.

If there are no functional subsidies policies, S_{m^2} and S_{kwh} are set to zero. Total PV output PVO is given by

$$PVO = I \times PQ \times PV\varepsilon \times RS \tag{8}$$

where $PV\varepsilon$ is PV efficiency, RS is roof size, PQ is the patch-quality (landscape quality) and depends on topography and prevailing climatic conditions, and I in W/m^2 is the insolation and is given by

$$I = 600 + \left[1000 \times pr \times \frac{(1 - \cos\theta)}{2}\right] \tag{9}$$

where θ is the orientation angle while pr is the particle reduction factor, a factor used to calculate reduction in aerosol particles which scatter solar radiation. It depends on location and prevailing climatic and weather conditions.

To be allowed to join a communal grid, a house must have installed PV of a given minimum capacity (power-threshold) and be within a given sensing radius of other homes with PV that meet the power-threshold. The idea to join a communal grid (CgD) returns true if

$$\frac{HCgPT_{CSR}}{TH_{CSR}} \times 100 > CgT \tag{10}$$

where $HCgPT_{CSR}$ is the number of houses with PV within a given communal grid sensing radius that meet the power-threshold ($CgPT$), TH_{CSR} is the total number of houses within the same sensing radius, and CgT is the communal grid neighbourhood threshold, minimum percentage of neighbours with PV that meet the $CgPT$ required within the sensing radius for a household to think about joining a communal grid. Communal grid sensing radius (CSR) is the radius within which a household can sense its neighbours. It depends on location and population density.

3 RESULTS AND DISCUSSION

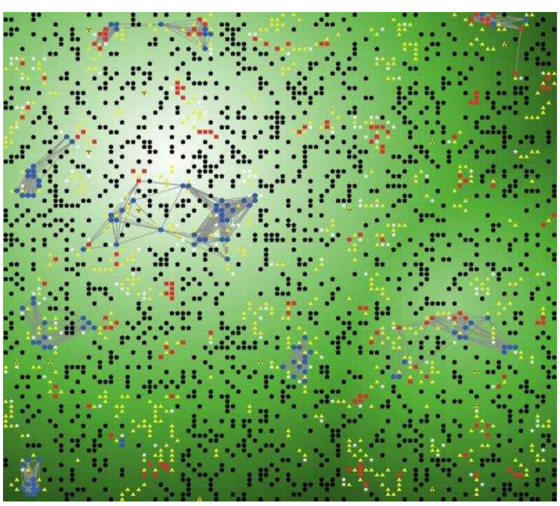

Figure 1: A View of the World after Simulations

Figure 2 shows a comparison of households with PV, households connected to communal grids, and households connected to the national utility grid after 25 years. Initially 347 households are allocated PV of various sized to mirror Kendu Bay area of Kenya. This represents 4.7% of all households in the area. Similarly, 229 households are connected to the national grid, representing 3.1% of all households. Communal grids are initially set at zero as none currently exists in Kendu Bay. After 5 years, the number of households connected to PV-based communal grids would have surpassed the number of households connected to the national-utility grid, indicating preferences for PV-based electrification systems. After 25 years, 4,325 households would have installed PV of various sizes, representing 44.1% of all households in the area, and 76.6% electrified households. Households connected to communal grids would have grown to 2,410, representing 24.6% of all households. On the other hand, households connected to the national grid would have only grown to 1,323, representing 13.5% of all households and 23.4% of all electrified households. It is noteworthy that after 25 years, 5,648 households would have been electrified, representing 57.6% of all households.

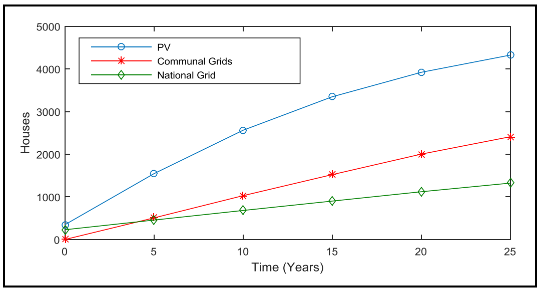

Figure 2: Different Electrification Topologies after 25 Years

3.1 Impacts of subsidies on PV diffusion

Studies show that positive government incentives and subsidies are largely responsible for rapid growths in PV installations in developed nations which have proper market and technical infrastructures necessary for implementations of such policies; Beise's research on diffusions of technologies across national boundaries found that positive government policies significantly stimulated diffusion of PV across many countries, underscoring the importance of government intervention in adaptations of new technologies [4]. A comparable study by Guidolin et al also found that positive government policies in forms of incentives and subsidies positively influenced PV diffusions across 11 countries [5]. Wustenhagen found that positive government policies, especially feed-in-tariffs (FiT), were largely responsible for the boom in PV installations in Germany [6]. Zhang et al found that in addition to positive regional governments' policies, costs also played significant roles in PV diffusion across Japan [7]. In developing nations on the other hand, limited resources restrict governments' abilities to subsidize new technologies as priorities are given to crucial projects. In this section, impacts of subsidies per kWh of PV electricity generated and subsidies per m^2 of PV Installed on the diffusions of PV microgeneration systems in Kendu Bay area are investigated.

Figure 3 shows a comparison of households with PV, households connected to communal grids, and households connected to the national utility grid after 25 years as a function of increasing subsidies/kWh of PV electricity generated. With no subsidies, 4,325 households would have installed PV after 25 years, representing 44.1% of all households. 2,410 households with PV would have connected to various communal grids, representing 24.6% of all households, while 1,323 households would have connected to the national utility grid, representing 13.5% of all households.

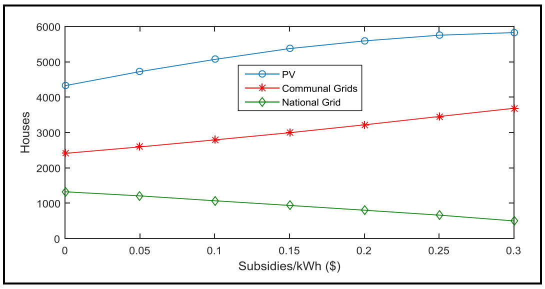

Figure 3: Impacts of Subsidies/kWh

With a subsidy of $0.30/kWh, 5,827 households would have installed PV after 25 years, representing 59.4% of all households, and an increase of 34.7% in PV installations. Similarly 3,685 households would have connected to communal grids, representing 37.6% of all households and an increase of 52.9% in communal grid connections. On the other hand, the number of households electriying through the national grid would have fallen to 499, representing 5.1% of all households.

Figure 4 shows a comparison of households with PV, households connected to communal grids, and households connected to the national utility grid after 25 years as a function of increasing subsidies/m^2 of PV installed. With no subsidies, 4,325 households would have installed PV after 25 years, representing 44.1% of all households. 2,410 households with PV would have connected to various communal grids, representing 24.6% of all households, while 1,323 households would have connected to the national utility grid, representing 13.5% of all households. With a subsidy of $150/$m^2$, 6,012 households would have installed PV after 25 years, representing 61.4% of all households, and an increase of 39% in PV installations. Similarly 3,689 households would have connected to communal grids, representing 37.6% of all households and an increase of 53.1% in communal grid connections. On the other hand, the number of households electriying through the national grid would have fallen to 701, representing 7.2% of all households.

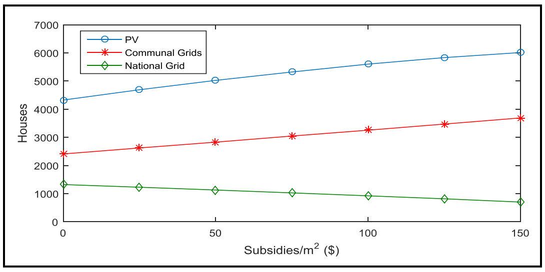

Figure 4: Impacts of Subsidies/m^2 after 25 Years

Table I below summarizes the above information.

Houses after 25 years	Subsidies/kWh ($)		
	0	**0.15**	**0.30**
Houses with PV	4325	5374	5827
Connected to Communal Grids	2410	2994	3685
Connected to National Grid	1323	937	499
Houses after 25 years	**Subsidies/m^2 ($)**		
	0	**75**	**150**
Houses with PV	4325	5321	6012
Connected to Communal Grids	2410	3046	3689
Connected to National Grid	1323	1027	701

Table I: Impacts of Subsidies on PV Diffusion

3.2 Impacts of neighborhood influence on PV diffusion

It is difficult to model the impacts of different non-quantitative social aspects on the adoption of a new technology. However, measurable parameter such as sensing-radius, the radius within which a household can 'sense' its neighbours, can be modelled and varied to explore the impacts of such parameters on the adaptation of a new technology.

Figure 5 shows a comparison of households with PV, households connected to communal grids, and households connected to the national utility grid after 25 years as a function of increasing sensing radius. At the default sensing radius of 500m, based on kendu Bay survey data, 4,325 households would have installed PV after 25 years, representing 44.1% of all households. 2,410 households with PV would have connected to various communal grids, representing 24.6% of all households, while 1,323 households would have connected to the national utility grid, representing 13.5% of all households. If the sensing radius is increased to 2 km, 5,204 households would have installed PV after 25 years, representing 53.1% of all households and an increase of 20.3% in PV installations. Similarly, households conected to communal grids would increase to 3,092 representing 31.5% of all households and an increase of 28.3% in communal grid connections. On the other hand, the number of households electriying through the national grid would have fallen to 831, representing 8.5% of all households

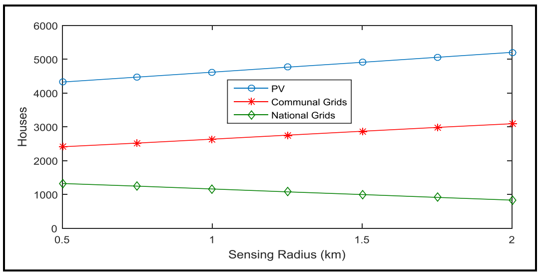

Figure 5: Impacts of Semsing Radius after 25 Years

3.3 Model Validation

Empirical PV installations data from 1985 to 2010 obtained from the Kenya's Ministry of Energy and Petroleum for two separate locations with similar geolocation data to Kendu Bay, i.e. Homa Bay and Ahero [8], are used to validate the model. The two towns were also chosen because in 1985, their populations of 31,063 (Homa Bay) and of 26,322 (Ahero) mirrored that of Kendu Bay (29,518) in 2014 [9]. Moreover, both areas are mainly occupied by people of the same ethnic and cultural backgrounds as Kendu Bay and would thus respond similarly to given social and cultural factors. The PV installations data are obtained by the government from retailers who also perform the tasks of installing and repairing the purchased systems. Figure 6 shows a plot of empirical and simulated PV installations data after 25 years. For Homabay and Ahero, 1985 is taken as year zero while 2010 is taken as year 25. For Kendu Bay, year zero is 2015 and year 25 is 2040. The plots show similar trends in PV installations, with Kendu Bay having mo PV installations due to falling PV costs. The plots validate the model.

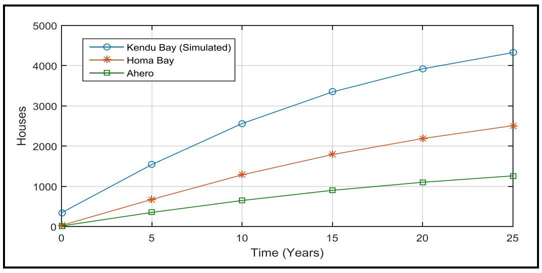

Figure 6: Empirical and Simulated PV Installations

4 CONCLUSION

In this work temporal diffusion of PV microgeneration systems in a typical rural Sub-Saharan developing community, Kendu Bay area of Kenya, are modelled and simulated using an agent-based model developed in Netlogo. Results show that after 25 years, more households will be electrified through PV systems of various sized than through the national grid. Specifically, results show that electrification rate in the area will steadily rise from current 7.8% to about 57.6%. Of these, 44.1% will be electrified through PV systems, with 24.6% being connected to communal grids. Another 13.5% will be electrified through the national grid. Introduction of subsidies would see further increases in households installing PV systems, leading to big rise in electrified households. Similarly, increasing neighbourhood influence, modelled as sensing radius, would lead to increased PV installations and subsequent communal grid connections.

4.1 Acknowledgement

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4.2 References

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