Improving Rural Electricity System Planning: An Agent-Based Model for Stakeholder Engagement and Decision Making

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Abstract

Energy planners in regions with low rates of electrification face complex and high-risk challenges in selecting appropriate generating technologies and grid centralization. To better inform such processes, we present an Agent-Based Model (ABM) that facilitates engagement with stakeholders. This approach evaluates long-term plans using the cost of delivered electricity, resource mix, jobs and economic stimulus created within communities, and decentralized generation mix of the system, with results provided in a spatially-resolved format. This approach complements existing electricity planning methods (e.g., Integrated Resource Planning) by offering novel evaluation criteria based on typical stakeholder preferences.

We demonstrate the utility of this approach with a case study based on a “blank-slate” scenario, which begins without generation or transmission infrastructure, for the long-term rural renewable energy plans of Liberia, West Africa. We consider five electrification

strategies: prioritizing larger populations, deploying large resources, creating jobs, providing economic stimulus, and step-wise cost minimization. Through the case study we demonstrate how this approach can be used to engage stakeholders, supplement more established energy planning tools, and illustrate the effects of stakeholder decisions and preferences on the performance of the system.

Keywords: Developing Countries, Agent-Based Modeling, Policy Planning, Rural Electrification

1. Introduction

This work provides an Agent-Based Model (AMB) for planning electrification efforts with the main objective of engaging policy makers in less industrialized countries (LIC). We refer to the model as *BABSTER* (Bottom-up Agent-Based Strategy Test-kit for Electricity with Renewables). *BABSTER* complements traditional energy planning methods by considering decision-making strategies and stakeholder preferences that are not limited to cost minimization outcomes. The framework provides more realistic insights given that policy is often developed based on a balance of several objectives. The tool considers technical, social, and environmental aspects, while exploring real word considerations such as value judgments and imperfect incentives.

BABSTER is not a substitute for electricity planning tools such as Integrated Resource Planning (IRP). Instead, it can be considered as a precursor to a full IRP or a supplement for its use. The tool supplements IRP by allowing stakeholders to investigate the results of their decision strategies in a quick and flexible manner. The framework was specifically built for developing countries where infrastructure and energy options are not already present.

In the remainder of this section we offer brief background on energy planning, *BABSTER*, and the case study of Liberia, West Africa. The Methods section explains the construction of the model, its components, and its dynamics as well as detailed information for the case study analysis. The Results section provides results generated using the model for the case study of Liberia. The Discussion section gives insights into the Liberian case study and also

provides an analysis of the use of the model and its possible benefits. We close the paper with a Conclusions and Policy Implications section.

While the results for the Liberian case study are important and relevant to policy makers in that country, the main contribution of this work is the general model that can be used in decision-making sessions to aid policy formulation around deployment of rural renewable energy options.

1.1. Energy Planning

A common approach for long-term electricity planning in developed countries is IRP. It develops a comprehensive plan to meet energy demand by considering available supply and demand side resources [1] and minimizing long term electricity costs [2]. This approach is often data intensive and is mostly done by utility companies regulated by government agencies. Some states in the USA mandate its use and, while not wide spread in developing countries, literature suggests that IRP should be used there as well [1], [3].

In LICs, multi governmental organizations, such as the World Bank and the International Renewable Energy Agency, often provide assistance in creating energy plans using diverse modeling techniques. The Africa Energy Unit, part of the World Bank, uses a general algebraic modeling system to analyze two pathways towards electrification in Liberia [4]. Their analysis aggregates the larger Liberian electricity needs according to sectors of demand with a medium growth and a high growth scenario. Only certain energy generation technologies are considered and its focus is on the capital city of Monrovia and other select demand points. The results recommend a minimum cost fuel portfolio for each scenario along with the expected cost of electricity and possible supply gaps.

The approach taken by the Africa Energy Unit does not consider the possible contributions of decentralized generation to the general electrification strategy. As the report from the World Bank acknowledges, other efforts are required for the development of a rural electrification program to achieve universal electrification in Liberia according to the goals of the country [4], [5].

Other modeling techniques have been utilized in developing countries. Urban, Benders, and Moll found 40 different models used for energy planning in developing countries [6]. However, literature suggests that these energy planning models are biased towards the needs of developed nations and none of the present day models adequately capture the needs of LICs [6], [7]. Some of the issues detailed by Urban, Benders, and Moll [6] are the high data requirements and technical user skills required, lack of sufficient focus on renewable energy technologies and decentralized rural generation options, and the absence of imperfect, non-econometric drivers for decision making. On the other hand, Bhattacharyya and Timilsina [7] point to the need for tools that create scenarios for consideration instead of suggesting *one* path that should be followed.

Literature suggests that a variety of methods used in conjunction will provide a broader base of data for stakeholders to make decisions and is a better alternative than any single model [8]. BABSTER is not intended as a final solution for energy planning in developing countries. Instead, it is offered as a framework for engagement with stakeholders to evaluate possible policies. In particular, this framework can be used as a pre-cursor or supplement to IRP and other more comprehensive exercises. The tool presented here is a good first step towards stakeholder engagement and system understanding while it also attempts to address the issues from [6], [7] mentioned above.

The main benefits of this approach are that it allows for stakeholders to conceptualize their decisions in a concrete manner, provides graphical user interphases (GUIs) for data input and visual outputs more amenable to a participatory process than “black-box” mathematical solutions, and provides quick, easy, and transparent scenario modification.

Given the benefits of the framework, one can envision using it in the stakeholder engagement phase of IRP development. The model interface (Figure 1) provides ample opportunities for stakeholders to change parameters including costs, peak and base demand, general shape of the load curve, and decision preferences. Results are shown graphically through a GIS. This allows consideration of an initial large number of scenarios that can be quickly narrowed to promising ones for more detailed analysis. It can also identify data gaps required for full IRP implementation. Finally, it can incentivize stakeholder buy-in through a clear and transparent presentation and interactive process.

To demonstrate BABSTER’s utility, the example of rural residential electrification in Liberia, West Africa is presented. The results show how different decision strategies shift fuel portfolios, the cost of electricity, the level of decentralization, job creation, possible economic inflows within a community, and capital investments required, allowing for more informed understanding of the system, balancing outcomes, and preparing informed strategies.

1.2. Agent-Based Modeling

Analysis of socio-technical systems in which humans interact heavily with technical components has been gaining traction as an application of the field of Complexity Science to different problems [9]. Complexity Science seeks to understand how the interactions

between small entities can result in the complex macro-scale behavior of systems that in some cases, learn, adapt, and evolve [10].

Agent-Based Modeling (ABM) is a platform useful for socio-technical systems [11]. ABM conceptualizes the components of a system and their interactions instead of producing a macro-level mathematical model. To do this, computer “agents” are created that represent the small level components of the system. They are placed in a computer environment or “world” and are provided with rules to interact with each other and their environment.

ABM should not be used as a predictive tool but as a scenario generation package [12]. Policies and stakeholder preferences can be easily introduced into ABM as exogenous rules for the agents to create simulations of interest. In this way, ABM can mimic stakeholder inputs [13], allowing practitioners to include the social context in which systems are evolving and making it a low cost test bed for policy and planning scenarios [14]. The simulations allow “*in-silico*” experiments impossible to conduct on the real system.

1.3. Liberian Case Study

As of the census of 2008, Liberia, West Africa, has a population of 3.47 million people, over 70% of them in rural areas [15]. The country has an area of 111,370 km² [16]. Less than 1% of the population in Liberia has access to electricity, paying the highest rate in the Sub-Saharan region, at \$0.43/kWh [4]. A central grid serves the capital city of Monrovia through high-speed diesel generation [4]. New projects are being pursued that intend to expand the country’s electricity grid through increased diesel generation, refurbishing a heavy fuel oil facility, reconstructing a hydro-electric facility, and connecting to the Western Africa Power Pool (WAPP) [4]. Even with successful implementation of these

projects, more than 50% of the rural population in Liberia is not expected to have access to electricity by the year 2040 [4]. The proposed projects depend largely on fossil fuels, a centralized structure, and reliance on the WAPP. Pineau has questioned the possible success of the WAPP as it requires a level of collaboration among nations in the region that has not been successful among other regions of the world with more developed energy infrastructure and higher institutional capacity [17].

The government of Liberia has issued policies that support additional electrification efforts beyond the centralized scheme. The National Energy Policy issued in 2009 proposes the goal of universal access to modern energy services in the country [18]. The Rural Renewable Energy Agency (RREA) was established in 2010 [4]. RREA is charged with administering the electrification of the rural areas using modern energy services [19]. RREA is in the process of establishing a rural electrification master plan. BABSTER could serve to facilitate the beginning stages of this process and encourage stakeholder engagement and buy in.

For this case study, only renewable energy sources are considered. In addition to being able to help meet environmental objectives set forward by the government, renewable energy sources are the most likely to serve these rural populations, characterized by low population density and lack of reliable infrastructure necessary to support transport of fossil fuels to rural areas. It also provides a window into policies that can be used for leap-frogging over centralized fossil based systems to achieve rural electrification in LICs.

2. Methods

2.1. Stakeholder Consultations

Two sets of consultations were conducted with Liberian energy sector stakeholders to develop this model. Table 1 lists the stakeholders that were included in these discussions. Consultations consisted of one-on-one visits with individual organizations. In the first set of visits, we provided each organization with an explanation of the basic modeling concept and ideas for possible strategies in electrification. Organizations provided feedback, data, and suggestions to be incorporated in the model.

We created a “proof-of-concept” model, which stakeholders evaluated during a second set of visits. During this time period, we provided the stakeholders with a short presentation of preliminary results. The model GUI was used to demonstrate samples of strategies to the organization representatives. The stakeholders again provided feedback on the usefulness of the model.

One of the main methodological choices that resulted from stakeholder feedback was to focus on the rural regions of the country and not include the capital city of Monrovia, due to current policy structure and existing grid expansion plans. This feedback has shaped the development of the case study presented here.

2.2. General Model Description

The ABM framework was created in Netlogo [20]. The model uses five agent types: Environments, Production Units, Populations, Lines, and Central Observer. For clarity

model components are capitalized to distinguish them from real world counterparts. Figure 2 provides a schematic of the Environment makeup and the agents' roles in the model.

These agents interact to achieve universal electrification, considering two main questions:

1. What resources should be deployed?
2. What transmission connections should be made to the resource?

We consider five possible strategies to answer these questions. The strategies differ in the priorities that the Central Observer has to deploy its resources and build connections. The five priorities are electrifying larger populations (LP), using the largest resource available (LR), creating new jobs (JC), generating economic inflows within communities (EI), and step-wise cost minimization (SCM). For the first two strategies, one resource is deployed and transmission is built until the resource is exhausted. For JC, EI, and SCM strategies, multiple resources can be deployed simultaneously. The Observer deploys an initial resource but then considers deploying other resources if they can maximize jobs (JC) and income (EI), or minimize costs (SCM) when compared to available transmission options.

The Observer initiates the simulation by creating a Production Unit in an Environment using a resource that fulfills the objective of the strategy. For the LP strategy, the Observer chooses the Environment and technology that provide the cheapest levelized cost of electricity (LCOE) for the largest Population Agent. For the LR strategy, the Observer deploys a Production Unit in the Environment with the largest energy potential. For the JC and EI strategies, the Observer picks the Environment and the technology in that Environment that produces the maximum jobs or the maximum economic inflows per

dollar invested within the community. In the SCM strategy the Observer starts with the resource that can provide the lowest LCOE. Figure 3 shows a schematic of the resource deployment framework and more detail is included in the *Decision Strategies* section.

Technologies considered for the Liberian case are photovoltaics (PV) with energy storage back-up, biomass combustion, and run-of-the-river hydro. All of the technologies are evaluated in a way that makes them dispatchable. Wind is not examined due to its low potential away from coastal areas [4], [21]. The model calculates levelized cost of electricity (LCOE), decentralized generation mix (DGM), fuel portfolio, jobs and economic inflows created, and capital costs of transmission, generation and storage. A detailed description of these calculations is included in the *Model Dynamics* section.

2.3. Model Components

2.3.1. Central Observer Agent

The Central Observer Agent can be understood as a central planner or decision maker. Through this agent, the model executes the decision strategies.

2.3.2. Environment Agents

Environment Agents make up the World in which the simulations take place. They contain energy resources and geographic data. GIS layers provided by the Liberian Institute of Statistics and Geographical Information Systems (LISGIS) are used to create these Agents. Environment Agents have access to hydrological, biomass, and solar data included in the World, as shown in Figure 2.

GIS data is matched to the Netlogo World, a square of 51 x 51 Environment Agents. Environments cover an area of 89.45 km² each. LISGIS created shape files for the political

subdivisions of Liberia, including, in descending order, counties, districts, clans, and tribes. Environments include their corresponding county and district. Lower subdivisions are omitted due to lack of disaggregated inhabitant data at those levels [15].

Because the resources are being planned as dispatchable, solar potential is established by using data for the rainy season in Liberia. Environments receive 4030 Wh/m²-day of insolation [22]. It is assumed that only 5% of each Environment's area is available for solar projects. We include a sufficient amount of energy storage to allow solar generation to offer energy and capacity services comparable to the other resource options. This is discussed further in the *Production Unit Agents* section below.

Biomass potential from food residue and cash crop residues in direct combustion applications is considered. This avoids using potentials from industrial activities and energy crops expected but not yet established in Liberia. Avoiding resources from these possible future activities allows the model to focus on the present situation and on feedstock more suitable for small, decentralized generation. To determine the biomass potential, national data for Liberian crop production is used [23] and the methods in [24] for disaggregating residues at the county level are followed. Tables with calculations for county level residue potential can be seen in the supplementary information.

Costs for biomass electricity production are affected when transporting fuels more than 32 km and distances beyond 160 km make fuel transportation costs prohibitive [25]. Each Environment has access to the biomass potential of its neighbors up to two parcels away. This makes the maximum distance 33 km, and transport costs are assumed negligible and not included in the cost estimates. Neighbors whose resources are used by an Environment

lose the opportunity to deploy those resources themselves, reducing their biomass potential to zero. A schematic of this concept can be seen in the supplementary material.

Twenty four sites identified with small to medium hydro potential (<50 MW) are included in this study [4]. A schematic of these locations can be seen in supporting material S2. A few larger sites existing in Liberia are excluded due to their consideration in the Monrovia grid or their requirement for larger civil infrastructure or bilateral agreements with neighboring countries, which changes the scope of the technologies considered.

2.3.3. Population Agents

Population Agents represent residential demand centers. A Population is created in the centroid of each GIS district shape in the LISGIS data. The Population Agents contain the information for the inhabitants of that district and it is assumed that there are 7 people per household [15]. Figure 4 shows a schematic of the Population Agent construction in the model.

Recent data collected by RREA was used to establish electricity demand per household as seen in Table 2 [26]. These data consider the number of appliances and time of use for each appliance in rural areas of Liberia resulting in estimated demand of 379 kWh/yr.

Because of the impact of the shape of the load curve on the size of generators, load factors, and associated costs, the data from RREA was used in Table 3 to develop a representative load curve.

The estimated peak demand for Liberian rural households is 191 W with a four-hour duration and a secondary peak occurring in the mornings of 100 W for one hour. We

assume that the off peak hours will present a small level of base demand resulting in a total demand per household of 449 kWh/yr, slightly greater than original RREA estimates.

The resulting daily load curve is shown in Figure 5. This load curve determines the utilization of selected resources, which influences their capacity factor and, for solar, the magnitude of energy storage needed to reliably meet load in real time. The shape of the theoretical load curve matches the shape found empirically in other rural villages of Sub-Saharan Africa [27]. This load curve is used to develop Equation 1.

$$e_G = l_s * t_s + l_p * t_p + l_b * t_b \quad (\text{Equation 1})$$

and

$$l_s = l_p * s$$

$$l_b = l_p * b$$

where

e_G = electricity demand in kWh per household

l_s = secondary peak load

l_p = peak load

l_b = base load

t_s = duration of secondary peak

t_p = duration of peak

t_b = duration of base load

s = ratio of the secondary peak load to the peak load

b = ratio of the base load to the peak load

2.3.4. *Production Unit Agents*

Production Unit Agents represent a power plant that uses the resources in a patch to create electricity. They inhabit an Environment Agent and use the resources that correspond to the Observer's preferences. Production Units are associated with operation and maintenance costs, fuel costs, duty factors, and efficiencies for the resource they use. These parameters can be seen in Table 3.

There is a wide difference in costs among world regions and within regions reported in the literature for the parameters in Table 3 [28]. Because of this the references used consist of work focused on developing nations and when possible in the Sub-Saharan African region or Liberia in particular.

Environment Agents can only host one Production Unit. Production Units make calculations on the maximum dispatchable power in each Environment and the necessary storage according to the load curve peaks and the available insolation. Equation 2 is used to calculate the maximum dispatchable solar potential. Equation 2 assumes that all energy required has to be stored in the battery. This is a conservative assumption used only in the estimation of the maximum energy available in the Environments. Cost calculations do not make this assumption as some of the energy is provided directly from the solar panels to the load bypassing the battery. Relaxing this assumption does not significantly change the results.

We consider biomass to be a dispatchable resource. The Production Units are sized so that they can meet the peak demand of the Population Agents. It is assumed that the storage costs of biomass are implicitly included in the capital and O&M costs for the technology.

Hydro potential considers only options for run-of-the-river projects. Inability to build storage mechanisms increases the risk of intermittency for this technology. Liberia has two main seasons with a dry period from November to April [16]. To ensure that hydro generation is available on demand, only the available flow during the dry season is considered. This is close to 30% of the maximum capacity according to two hydro projects being studied in Liberia at Mount Coffee and Mein River [4], [29]. This reduces the capacity of the site but provides a safety margin for determining available year-round generation.

There is a risk with this approach that in dry years the hydro sites might experience a loss of service. The model assumes appropriate load management measures would be introduced for hydro technology minimizing these risks. Similar instruments controlling the peak demand are already in use for small hydro projects in Liberia [29], [30]. Connections are provided based on maximum power consumption per household. This permits developers to artificially cap the peak demand in a way that increases the probability to supply it with the minimum expected potential.

$$l_{pmax} = \frac{\eta_b * i * A_{max} * \eta_p}{(t_s * s + t_b * b + t_p)} \quad (\text{Equation 2})$$

where

l_{pmax} = maximum peak load that can be serviced in kW per patch

η_b = battery round trip efficiency

i = insolation in $\frac{Wh}{m^2-day}$

h_s = average hours of sunshine per day

A_{max} = maximum area available for solar panels in m^2

η_p = efficiency of solar panels

Equation 3 is used to calculate the storage required per kW of dispatchable solar.

$$S_R = \left\lceil \frac{(t_s * s + t_b * b + t_p - h_s * b)}{\eta_b} \right\rceil \quad (\text{Equation 3})$$

where

S_R = storage required in h

2.3.5. Line Agents

Line Agents represent transmission lines connecting Production Units and Populations and carrying the electricity load. Transmission lines can connect Populations directly to a Production Unit or can connect an unelectrified Population to an electrified Population connected to a Production Unit with untapped capacity. Transmission lines can be of different voltage classes and costs depending on load and distance as seen in Table 4.

Line losses of transmission infrastructure are not considered. The capital costs for building transmission lines including the building of substations, project management, and overhead can be substantially higher than the material price for the lines. A recent project in Kenya shows transmission costs can more than double when considering overhead, management, and outreach efforts associated with electrification [31]. For the case study the assumption is made that materials costs are 40% of total installed costs according to data found in [31], [32]. Appropriate data for these costs in Liberia should be determined

in the future. However, simulations for scenarios with lower costs for installed transmission show that there is no change in the general trend of the results.

2.4. Decision Strategies and Model Dynamics

The strategies are chosen to demonstrate possible priorities and tendencies seen in the literature. For example, in the developing world there is a focus on provision of infrastructure and services in areas of high population or urban areas [6], [7]. Many recent renewable energy projects are formulated due to the presence of a large resource, such as the concentrating solar farm of Ivanpah in the California desert, despite their isolated location [33]. Providing jobs and generating income are often touted as strong benefits of developing renewable resources and providing electrification [34]–[36]. Finally a deployment of multiple resources in a decentralized scheme is proposed as a more economical option to traditional centralized grid extension plans, in particular for the level of demand expected in the case study presented here [37], [38].

The data used for calculating jobs and economic flows created from electricity production can be seen in Table 5. The data in Table 5 pertain to the production of inflows and jobs within the community and not at the global scale. The references estimate that mini-hydro technologies produce no economic flows within communities. Because hydro does not have an associated cost for fuel and its maintenance is relatively low, few economic transactions occur within the community after the installation of the project is finished.

Correspondingly, we assume that the investments in transmission infrastructure do not create jobs or economic inflows within a community. This is not true at the national scale, where such investments will likely result in increased jobs and economic activities that will not impact the communities directly.

The Observer makes decisions at each time step by comparing all its options considering the strategy. For the LP and LR strategy, the Observer considers the closest point where the grids with capacity can be extended. For the JC and EI strategies, the Observer considers all possibilities for grid extension or new generation resource deployment and selects the option that maximizes jobs or income generated per dollars invested. Finally, for the SCM strategy, the Observer considers all options for grid extension and new generation and chooses the lowest LCOE option.

As the model progresses and the existing networks expand, the Observer finds situations where the existing Lines have to be upgraded to carry the load demanded according to Table 4. In these cases, the cost of upgrading the lines is included in the LCOE calculations.

The following equations are used to calculate the costs of connections or decentralized generation for each technology.

$$LCOE_{j-i}^T = \frac{UCC_t * CRF_t}{D_f * 8760 \frac{hrs}{yr}} + \frac{(d_{j-i} * TCC_{j-i} + CNU) * CRF_{trans}}{Q_{j-i}} + \frac{O\&M_T}{D_f * 8760 \frac{hrs}{yr}} + \frac{PL * FC_t}{HR_t * \eta_t * 278 \frac{kWh}{GJ}} \quad (\text{Equation 4})$$

where:

$LCOE_{j-i}^T$ = levelized cost of electricity for supplying population j from Environment Agent or existing network i in \$/kWh with technology T

UCC_t = unit capital cost of technology T in \$/kW

CRF_t = capital recovery factor for technology T

D_f = load factor established by the load curve or

$$D_f = \frac{(t_s * s + t_b * b + t_p)}{24}$$

d_{j-i} = distance of shortest path between Population j to Environment Agent or Production Unit i in km

TCC_{j-i} = transmission capital cost in \$/km according to Table 4

C_{NU} = cost of network upgrade if any

CRF_{trans} = capital recovery factor for transmission infrastructure

Q_{i-t} = electricity carried by the shortest path between Environment Agent or Production Unit i and population j in kWh

$O\&M_T$ =operation and maintenance cost for technology T in \$/kW-yr

PL = price levelizing factor for fuels

FC_T =fuel cost for technology T in \$/ton if any

HR_T =heat rate of technology T in GJ/ton if any

η_T = efficiency of conversion of technology T

and

$$CRF_t = \frac{r}{1-(1+r)^{-n_t}} + t\&i$$

where

r = effective discount rate assumed as 12%

n_T =life time for of technology t in years assumed as 25 for solar [28] , 2.5 for energy storage [26] , 40 for transmission infrastructure, and 30 for all other technologies

$t\&i$ = taxes and insurance assumed as 3%

$$CRF_{trans} = CRF_t \text{ for } n_t = 40$$

and

$$PL = \frac{r}{r - 0.02}$$

and

$$C_{NU} = \sum_{UL} \Delta TCC_{UL} * d_{UL}$$

where

ΔTCC_{UL} = change in price for links requiring upgrade in \$

d_{UL} = span of links requiring upgrades in km

In the case of solar technology the cost of storage is included by adding Equation 5 to Equation 4 above.

$$LCOE_S = \frac{UCC_B * CRF_B * S_R}{D_f * 8760 \frac{hrs}{yr}} \quad (\text{Equation 5})$$

where

$LCOE_S$ = levelized cost of electricity component for storage in \$/kWh

UCC_B = unit capital cost of batteries in \$/kWh

2.5. Model Simulations: Baseline and alternative scenarios

In the preparation of this case study a baseline scenario was developed with parameters taken from average values seen in Tables 3, 4, and 5 above. Other scenarios were evaluated to determine the model's response to changes in the parameters and demonstrate its ability for scenario building. Scenarios were built through one-at-a-time perturbation of

peak and base demand, transmission costs, solar and hydro capital costs, and biomass fuel costs. Also, round-robin peak and base demand changes were analyzed. A summary of the sensitivity scenarios can be seen below in Table 6.

We consider these scenarios as some of the most probable changes to occur for the Liberian case study. Changes in the peak electricity demand represent a situation where rural areas rapidly adopt electricity appliances following the same load curve shape presented above. Base Demand changes represent situations in which the available idle capacity during the day is exploited. This can be achieved by small home based enterprises, local clinics, schools and other services, or by new industries being established such as animal feed production or grain milling. While the model considers only residential demand, selling this excess capacity to other sectors might be a desirable policy as a type of subsidy for the residential sector. As mentioned earlier the transmission costs in Liberia may be different from those found in the literature. The scenarios here represent possible reductions in cost that may be achieved through management but also extreme scenarios that represent only the cost of materials. Solar capital costs for generation and storage are rapidly declining [28]. The scenarios presented here explore reductions that are feasible in the near future. The biomass fuel cost scenarios explore a situation where the cost of cash and food crop waste rises with the increase in demand for the feedstock. Finally the hydro costs used in the baseline scenario correspond to the small run-of-the-river project on the Mein River in Bong County [29], [30]. Significant reductions in those costs can be achieved by using local industries or know-how [28], [39]. The values presented here explore these possible reductions in capital costs.

2.6. Model Verification and Validation

Model verification and validation are critical steps for the development of simulations, in particular for ABM where standard practices are still developing. Model *verification* determines whether the computer software is performing the tasks that the modeler intended it to [40]. Model *validation* refers to whether the model is capturing the behaviors of the real world system it is meant to represent [40]. For model verification and validation, the guidelines suggested by [40], [41] are used in this paper. Because model verification is more of a “proof-reading” function, specific modeling verification steps and computer code can be found in the supplementary information. The complete model code can be downloaded from modelingcommons.org.

Model validation is generally more challenging due to ABM’s framework of using micro-units and conceptualizations of human decisions. The following steps were taken for validation:

- 1) Micro-face validation: Agents and model sub-procedures were examined independently to ensure that their actions correspond generally to field observations and expected outcomes.
- 2) Macro-face validation: The macro processes and patterns developed in the model were examined to ensure that they follow expected behaviors in the observed system.

- 3) Corner Cases: This step is tied to the scenario analysis. Extreme values that should yield expected outcomes are used. For example, if the transmission costs are sufficiently high the decentralized generation mix in the system should increase, or if biomass capital costs are increased above all other technologies the share of biomass in the system should decrease. While extreme corner cases were analyzed we do not present them in the paper preferring to discuss the alternative scenarios mentioned above.
- 4) Stakeholder validation: This step involves consultation with stakeholder and experts in the field. Stakeholders are asked to engage with the model, its inputs, and outputs. The stakeholder engagement carried out for this case study is detailed above.

3. Results and Discussion

3.1. Baseline Scenario

Figure 6 shows the LCOE for each decision-making strategy. The LP and LR strategies result in \$0.39/kWh and \$0.38/kWh respectively. JC is the most expensive strategy resulting in \$0.62/kWh. The most economical strategies are EI, at \$0.24/kWh, and SCM at \$0.20/kWh.

The Mein River mini-hydro project in Bong county found Liberian willingness to pay for electricity to be \$10 per month per household [30]. Considering the baseline scenario presented here corresponds to 37.4 kWh/month this translates to a willingness to pay of

\$0.27/kWh. This means that the SCM and EI strategies are affordable for Liberians but the other cases would require a subsidy or other intervention to function economically.

Figure 7 shows the resulting resource mix for each strategy. Resulting fuel portfolios are dominated by biomass in the baseline scenario with exception of the JC strategy, which uses exclusively solar technology. Solar technology creates the most jobs per unit energy while biomass is generally the most abundant resource in Liberia and generates the most economic inflows per unit energy within a community.

Figure 8 shows the overnight capital investments for each strategy. LP, LR, EI and SCM require similar costs for generation because of the similarities of their fuel mixes. The JC strategy requires higher costs of generation and storage. While the costs per kW of biomass and solar PV are similar, solar technology requires higher generation investment. To supply 1 kW of peak demand more than 1kWp of solar has to be installed for charging of batteries.

One of the major outcomes of applying different decision strategies is the level of decentralization within the electric grid. The decentralized generation mix (DGM) measures how many separate sub-systems are being used. If a network has 100 demand points and 100 separate subnetworks are required to achieve full electrification, the DGM is 100%. If only 50 subnetworks are required then the DGM is 50%. More than one Production Unit may be needed to electrify one demand center or subnetwork, but since they would be connected in their own micro-grid the number of subnetworks would still be one. For example, if 100 production units were required to power 2 demand centers, but all of them are interconnected, they would form one subnetwork.

The DGM is determined by the strategy, which directly impacts transmission costs. In the baseline scenario, LP and LR strategies have a DGM of 1%, almost completely centralized. In general, the LP and LR strategies will result in more centralized structures due to their focus on exhausting a resource. In the Liberian case, the result is a complete central structure because the magnitude of the resources available is high compared to the demand. In other contexts, high demand or low resource potential may increase the DGM of these strategies, as resources can be exhausted more quickly.

The most expensive strategy, JC, has a DGM of 99% and uses solar technology exclusively. So while it is highly decentralized minimizing transmission costs, it requires significant investments for generation and storage. This strategy may not always result in complete decentralization. The results are highly dependent on the assumed parameters for transmission and solar technology's creation of local jobs. In a different context a stakeholder may assume that some fraction of the transmission related jobs can be local resulting in more transmission projects selected and a lower DGM. In the case of Liberia, there is homogenous insolation throughout the country. In other contexts, like the mentioned Ivanpah project in California, the solar resource is bound to a location and this may result in a larger centralization.

The EI strategy is a good comparison for a situation where a more moderate DGM would result due to geographic location. As opposed to solar, biomass is bound to specific sites. The EI strategy results in a DGM of 45%. Even though transmission projects in this case study do not contribute to local economic flows, the location of biomass may not be convenient for all demand centers. In those cases, increasing capacity at certain sites and using transmission to fulfil demand results in a better economic flow per dollar spent.

The SCM strategy has a DGM of 85%. Since the strategy is guided by LCOE, larger projects with transmission infrastructure can compete if the amount of electricity being transmitted reduces the cost per unit. This strategy will generally result in moderate centralization due to its focus on economic values that allow this type of project to compete.

Figure 9 shows GIS output for the baseline scenario illustrating DGM and summarizing the results in Figures 6-8 in a graphical manner.

Figure 10 shows economic annual inflows and jobs generated by each strategy. The JC strategy is the highest LCOE but generates the least amount of economic flows within a community. Its economic inflows are low because they represent the amount of money that stays within a community. Solar technologies may generate more economic activity but it usually represents money that does not stay within the community. Because of the labor situation in Liberia, decision makers may use this strategy or a hybrid of it, despite the higher associated costs. In 2010, less than 20% of the population in Liberia had a salary or wage job [42]. The generation of jobs may warrant a subsidy for solar technology implementation to bring it to an affordable range.

Alternatively, the other strategies generate more income within the communities. While this does not represent a stable job, the boost in economic activity may be more important depending on stakeholders' value judgments. At the same time the strategies provide a lower LCOE while generating some jobs. This may not be a generalizable result. In the case of Liberia, the abundant biomass allows generation of community economic flows in many of the strategies. In cases where biomass may not be as abundant, the opportunities to generate those economic flows may be limited.

Providing this kind of trade-off analysis is important. It allows stakeholders to craft policy in a way that does not focus on a prescribed minimum but expresses the options and considers other parameters important for the social reality of the country.

3.2. Alternative scenarios

3.2.6. Peak and Base Demand

Figure 11 shows the change in LCOE with changing peak and base demand. It is interesting to note that increases in demand generally result in decreases in LCOE. When base demand increases, reductions in LCOE are directly tied to better utilization of the energy generation investments. The load factor increases, as more electricity is required. Changes in peak demand bring better utilization of transmission investments when present as well as an increase in the load factor of generation equipment. While at certain points increases in electricity demand require upgrades to the transmission equipment, the benefits to load factor offset extra costs for the situations studied.

The SCM strategy is the most stable with respect to LCOE, remaining in a range of \$0.10-0.20/kWh. It remains stable by changing its resource portfolio and DGM. As the peak power increases results show that the SCM strategy reduces its share of PV and its DGM. A higher centralization allows it to increase the use of the transmission investments made keeping costs low. The SCM strategy is expected to be the most stable in other contexts as well due to its ability to choose technologies based on costs giving it a larger independence

from geographically bound resources. If a resource becomes uneconomical due to its location the strategy will choose a different technology that can reduce costs through proximity. This is not always the case with the other strategies where jobs, economic flows, or size are tightly bound to a particular technology.

3.2.7. Transmission Costs

The transmissions cost scenarios considered here do not result in significant changes. LCOE for all strategies increase slightly, with those strategies having a lower DGM suffering the sharper increases. There are no changes in jobs created, economic inflows, or fuel portfolios in any of the strategies except for the SCM strategy. As the costs of transmission increase SCM increases its share of hydro and PV, taking advantage of their location to stabilize costs.

3.2.8. Solar Capital Costs

Because most strategies do not use solar significantly, changes in solar capital costs did not result in changes to LCOE, jobs created, economic inflows, or DGM. The exceptions are the JC strategy and the SCM strategy. The JC strategy's LCOE drops with the reduced costs in solar capital investments. The SCM strategy incorporates slightly more solar in its fuel mix as solar costs are reduced, but its LCOE remains stable.

3.2.9. Hydro Capital Costs

The reductions considered here for hydro capital costs only affect the LP and SCM strategies. As the costs are reduced to \$1000/kW the LP strategy incorporates up to 13%

hydro in its fuel mix. Its LCOE increases slightly. This is because the initial investment in hydro that results in lower LCOE for a higher population then requires higher transmission investments as the strategy focuses on exhausting the resource deployed.

For SCM the share of hydro increases up to 28% with decreasing capital costs but its LCOE remains stable.

3.2.10. Biomass Fuel Costs

The increase in biomass fuel costs causes an increase in LCOE for all strategies except JC, which does not use biomass technology. The fuel portfolios of LR, JC, and EI remain stable. For LP and SCM, the increase in cost of fuel is enough to cause a reduction of biomass in the fuel portfolio. This capacity is replaced mainly by hydro. Figure 11 shows a tipping point at \$20/ton where hydro begins replacing biomass.

Buchanan Renewables, a company that invested in electricity generation in Liberia through biomass residues, paid \$2/ton for their raw materials, according to verbal communications with the authors. The World Bank however, estimates that the cost of local wood chips can be \$37-60/ton while importing wood chips from the U.S. results in a cost of \$95/ton [4]. These values would be in the range where hydro begins to displace biomass generation.

4. Conclusions and Policy Implications

This paper presents a framework, *BABSTER*, which can be used to engage with stakeholders in the development of renewable energy master plans while supplementing

and expediting other energy planning techniques. *BABSTER* is meant as a flexible tool to be used in early stages of the process to create what-if scenarios and not to prescribe an absolute path. This means that the framework can be useful in the development and evaluation of policy.

In particular, three characteristics allow the model to complement IRP and other energy planning models. First, IRP seeks to engage with stakeholders; *BABSTER* can increase the quality of those engagements. The graphical nature of the interface, the use of GIS displays, and the ability to change parameters quickly, could improve the interaction with stakeholders when developing a full IRP.

Second, *BABSTER* has been created with developing countries in mind. In developing countries universal electrification has not been achieved. Even where access is available power grids tend to present technical issues or fail to fulfill demand. *BABSTER* provides the option of examining these situations from the beginning. It also allows the consideration of theoretical load curves where demand has not been established. This is an important consideration when developing policy for rural electrification.

Third, *BABSTER* goes beyond econometric considerations. IRP focuses on minimizing the utility bills of a customer by using the resources available to utilities and other entities [1]. *BABSTER* can capture preferences and motivations that reflect other realities in a developing country. This would allow IRP to incorporate more of the social context in which the decisions are being made. This is important as policy is often created with imperfect incentives, and competing or complementary objectives in mind. The tool allows *in-silico* experiments for policy makers to evaluate their strategies at a low cost.

In general, *BABSTER* provides the opportunity for decision-makers to evaluate a wide body of scenarios. This responds to the call in the literature to provide stakeholders with a variety of information instead of prescribing optimum paths for development [8], [9]. Full consideration of the metrics provided by the framework can assist policy makers in making trade-off decisions. For example, the benefit of introducing a subsidy that would result in an increase in jobs, as is possible for Liberia.

BABSTER can be adapted to different regions through the use of GIS data. The ability to layer renewable energy potential, political divisions, demand centers, and cost data makes it a flexible asset for policy planning, capacity building, and the creation of renewable energy master plans in other regions.

Reality and context are very different among developing countries. Parameter data presented here are reasonable but best practices should be followed before using the model for national decision making. Country specific data should be obtained in collaboration with stakeholders. Corner-cases should be developed, with data ranges available, to understand the decision space. Performing these steps in a participatory manner with decision makers would bolster the reliability of the model for decision support.

4.1. Liberia Case Study

The Liberian case study provides insight into the blank slate scenario where no fossil fuels or existing infrastructure are used. The model shows that a dispatchable system of mini-grids is possible at an acceptable LCOE if the SCM strategy is chosen. This is supported by

other results on the literature, which show that in the case of Liberia a highly decentralized system provides the most economical approach [38].

Liberia has a high rate of unemployment at 80% in the formal sector and 64% of Liberians live below the poverty line [5], [43]. Government stakeholders may wish to incentivize jobs and economic inflows in the communities, particularly rural areas, which carry the majority of poor and formally unemployed. Using the JC or EI strategy tied to a subsidy or Clean Development Mechanism financing that can reduce the cost of electricity may be desirable. Policy makers may be more interested in incentivizing job creation and economic flows in the short term while expecting electricity demand to increase or demand side management to change the load curve and decrease the cost of electricity allowing a phase out of the subsidy.

The results also show that the peak demand and base demand have a high impact on the LCOE. A change to the load curve through connection of rural residential demand to productive uses during the off-peak hours could significantly change the cost to the residential sector and further incentivize the economy. This opens an opportunity for policies that integrate industrial, service, and commercial activities to the residential sector in order to offset costs for both parties.

In Africa, many industrial and service facilities engage in self-generation with diesel at a higher cost than the options considered here [44]. We have observed this as the norm in Liberia. Using the industrial facility as a load curve management tool for the residential sector may be interesting, in particular because of the presence of diesel backup at those sites. A similar arrangement is being used in the Mein micro-hydro project with Cuttington

University and Phoebe Hospital. These institutions have a considerable load served by in-house diesel generators [29], [30]. The project will displace the diesel production with the excess hydro generation when available, reducing the cost to the University and the hospital of their self-generation and the LCOE of electricity to the residential customers.

4.2. Future Work

In future work the model will be adjusted so that existing grids and fossil fuels can be used in the strategies. This would allow more realistic experiments for countries that already have a significant level of electrification. As presented here the model does not reflect those issues directly but one can imagine parallels to the decision strategies presented. For example, the fossil-based grid in Monrovia could be significantly expanded at a very low generation capital cost creating a resource larger than the biomass project in the present example. The LP and LR strategies would then deviate from each other as the present LCOE of fossil resources in Liberia is very high but LR would be bound to using high levels of that resource. This would result in low capital generation costs, higher transmission costs due to increase network length, and much higher LCOE due to operation, maintenance, and fuel costs of the resource.

Future work in Liberia will consider the use of the model for real policy planning sessions. The graphical interface and ABM's intuitive presentation allow for the tool to be used in game-like sessions. In these sessions policy makers can participate in the development of strategies and even take over agents in the model as the simulations take place. These exercises can also be considered as validation efforts falling in the area of expert validation outlined in the literature [40], [41].

Improving the quality of data, including more of the technical aspects and related costs of grid development, and enhancing considerations of renewable energy intermittency are necessary. In particular, better data for biomass and hydro potential is needed given their high promise for the Liberian scenario. Coastal wind options should be integrated due to the location of some significant population centers close to the coast. Integration with the larger primary grid evolving around Monrovia may also provide interesting policy opportunities and technical benefits. Renewable technologies with different peak production times may provide load management alternative for some portions of the grid with the grid acting as a backup to some of the population centers that could be integrated through smaller connections.

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Control Module

Output Module

Figure 1: Screen shot of model GUI. The graphical nature of the model allows for stakeholder interphase and encourages experimentation. The output module shows GIS representations of the environment, the demand centers, production units, and networks formed. It also shows reporters of importance such as the LCOE. The control module is used to change parameters in the model and quickly generate new scenarios.

GIS Data for Model Environment

Agent Roles in the Model

Figure 2: Schematic of the make-up of the model Environment through data layering (above), and of agent roles in the model (below). Notice that all environment agents are squares although their limits are not visible in the figure. Different colors in the Line agents represent different capacities. Production units have different symbols to represent their fuel. In the figure the green plant represents a biomass Production unit. The Central Observer interacts directly with the model environment but not with the individual agents.

Figure 3: General schematic of decision strategies

Figure 4: Population Agent construction schematic. Each shape formed by the light blue lines is a GIS representation of the Liberian districts. In the centroid of each shape a Population Agent (house) is created that represents the population in the district. Because this work focuses on rural populations Monrovia is excluded and the largest rural population, Kakata, is represented by the larger house in the picture.

Figure 5: Conceptualization of demand curve in Liberia

Figure 6: LCOE for Each Decision Strategy. SCM strategy results in the lowest cost. This is due to its flexibility in balancing the use of deployed resources versus the deployment of new ones depending on the transmission costs tied to the geographic locations of the resources and the demand points. The JC strategy has similar flexibility but depends on solar technologies to create jobs, which are expensive and require storage capital investment. While the LP and LR strategies differ only slightly, changes in the size of the resources or the population distribution may result in these strategies diverging significantly from each other. This was confirmed by simulations that explore changes in those parameters.

Figure 7: Fuel Portfolios for Each Decision Strategy. Note that Biomass is the most abundant resource in Liberia and it dominates the portfolios of most strategies. Solar creates the most jobs per unit of electricity, explaining its particular use in the JC strategy. The SCM strategy shows that for the, Liberian case, the inclusion of other resources to take advantage of their geographic location achieves a lower LCOE.

Figure 8: Overnight Capital and Transmission Costs Required for Each Strategy. Generation capital is similar for all strategies as it is largely dominated by the peak demand. JC is the exception as it is using very expensive generation equipment related to solar, which requires extra peak power installation to charge batteries. The low transmission capital investment is not enough to counter act the high generation costs. The SCM strategy is able to minimize the transmission investment resulting the lowest LCOE. While the LP and LR strategies use the same fuel portfolio, their LCOE is slightly different, a result of the transmission investment. This shows that the geographic location of the resources and the strategy used can impact the results. While the case shows only a slight difference, changes in the size of the resources could result in significant differences for these strategies.

Largest Population

Largest Resource

Job Creation

Economic Inflows

Step-Wise Cost Minimization

Figure 9: GIS output of model for baseline scenario of each strategy. Production Units are marked by red suns for solar, green plants for biomass, and blue drops for hydro. White lines represent 33 kV lines and green lines 138 kV. Higher capacity lines were not required in the baseline scenarios. Notice that the LP and LR strategies are completely centralized with only one production unit. Because of the data for Liberia the results of these strategies are very similar. However, the location of the production unit is different for both strategies. The presence of a larger resource elsewhere would change the results dramatically causing LP and LR to diverge. The JC strategy is completely decentralized. The EI strategy has a DGM of 45% completely based on biomass micro-grids. The SCM strategy has a DGM of 85% and a more varied portfolio. Notice the cluster of solar projects in the south east and a few hydro projects.

Community Economic Inflows

Jobs Generated

Figure 10: Yearly Economic Inflows and Jobs Generated by Each Strategy within local communities. Its important to note that the JC strategy uses solar technology due to its promising job creation capabilities. However, that technology does not generate high levels of economic flows within the communities due to its technical requirements, which result in economic flows out of the communities. For the Liberian case study, and future work, it is important to gather further measurements of jobs and economic flows generated in the context BABSTER will be used. Changes to those parameters may result in significant differences in the fuel portfolios and benefits sought with each strategy.

Figure 11: LCOE Change with Change in Peak and Base Demand. In general, increases in demand decrease LCOE. Higher use of the infrastructure reduces the cost per unit of energy used. Even with larger infrastructure required for higher peak demands, the increase in electricity usage offsets the costs reducing the cost per unit of energy. It is interesting to note the stability of the SCM, which can take advantage of decentralized deployment to maintain LCOE low from the beginning.

Figure 12: Change in hydro penetration with increasing biomass fuel costs. SCM is the Step Wise Cost Minimization Strategy and LP is the Largest Population Strategy.

Table 1: Stakeholders included in consultations

Governmental Organizations	Non-Government Organizations	Private Sector Organizations
<ul style="list-style-type: none">• Ministry of Land, Mines, And Energy• Liberian Electricity Company• Ministry of Public Works• Liberian Environmental Protection Agency• Rural Renewable Energy Agency	<ul style="list-style-type: none">• United Nations Environmental Program in Liberia• Center for Sustainable Energy Technologies• Winrock International, Liberian Party	<ul style="list-style-type: none">• Buchanan Renewables• Manitoba Hydro, Liberian Party

Table 2: Expected Electricity Use in Liberian Rural Homes

Appliance ^a	Use per day (hrs) ^b	Units ^a	Power Consumed per Unit (W)*	Morning use (hrs) ^b	Evening Use (hrs) ^b
Lighting	5	5	15	1	4
Radio	12	1	25	6	6
Portable DVD	4	1	25	0	4
TV	4	1	65	0	4
Phone Charger	4	1	1	0	4
Morning Peak (W)				100	1 hour duration
Evening Peak (W)				191	4 hour duration

^aData from RREA

^bAuthors' estimation

Table 3: Parameter Values and Sources for Cost Calculations

Parameter	Value	Sources
Small Hydro		
Hydro Capital Cost (\$/kW Installed)	2730	Average cost in pilot project in Liberia [35]
Hydro O&M (\$/kW-yr)	2% of capital	[34]
Hydro economic life (yr)	30	[34]
Small Biomass		
Biomass Capital Cost (\$/kW Installed)	1750	Median cost in Africa and Asia [34]
Biomass O&M (\$/kW-yr)	4.5% of capital	[34]
Biomass economic life (yr)	20	[34]
Biomass Fuel Costs (\$/ton)	2	[37]
Biomass Heat Content (GJ/ton)	17.5	[30], [38]
Conversion Efficiency (%)	25	For Developing countries [34]
Solar PV		
Solar Capital Costs (\$/kWp Installed)	1500	[32]
Solar economic life (yr)	25	[34]
Solar O&M (\$/kW-yr)	2% of capital	[32]
Panel Efficiency (%)	15	[34]
System Losses (%)	14	[39]
Battery Capital Costs (\$/kWh)	213	[32]
Battery economic life (yr)	2.5	[32]

Table 4^a: Line Voltage Class for Desired Loads and Distances

		Distance and Load Limits					
Line Rating	Installed Costs ^b (\$/km)	< 80 km	100 km	200 km	300 km	400 km	> 400 km
33 kV	57,500	14 MW	0	0	0	0	0
138 kV	225,000	156 MW	143 MW	117 MW	91 MW	68 MW	57 MW
230 kV	480,000	435 MW	399 MW	326MW	254 MW	188 MW	160 MW
345 kV ^c	720,000	1,275 MW	1,169 MW	956 MW	744 MW	552 MW	468 MW

^aLoadability limits were determined using data in [42]

^bMaterial cost data obtained from [22], [41] for 33, 138, and 230 kV and followed evidence from [40], [41] which shows material costs are 40-50% of installed costs.

^cModel results show that higher voltages are not required in the Liberian case

Table 5: Job and Economic Inflow Generation of Each Technology

Technology	Jobs Created^a (Job-years/GWh)	Economic Inflows^b (\$/MWh)
Solar	0.88	9.1
Biomass	0.21	36.8
Hydro	0.28	0

^a*Source* [46], [49]

^b*Source* [45]

Table 6: Sensitivity Scenarios

Scenario	Baseline Value		Sensitivity Scenarios		
Household Peak Electricity Demand (W peak)	190		150, 200, 250, 300, 350, 400		
Base demand (% of peak)	10		20, 30, 40, 50		
Transmission Line Costs (\$/km for materials. Material costs are 40% of installed costs)	Reduction from Baseline		20%	40%	60%
	33 kV	57,500	46,000	34,500	23,000
	138 kV	225,000	180,000	135,000	90,000
	230 kV	480,000	384,000	288,000	192,000
	345 kV	720,000	576,000	432,000	288,000
Solar Capital Costs	Generation (\$/kWp)	1500	1300, 1000		
	Storage (\$/kWh)	213	170.4, 127.8		
High Biomass Fuel Costs (\$/dry ton)	2		10, 20, 100		
Hydro Capital Costs (\$/kW)	2730		2000, 1500, 1000		