Biomass residues for power generation: A simulation study of their usage at Liberia's plantations

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Abstract

This study employs an Agent-Based Model (ABM) to simulate rural electrification in Liberia using biomass residues from Liberia's major rubber and oil palm plantations. The model is constructed using the NetLogo software (v 5.2.0) [1]. We evaluate the use of gasifiers powered by residues from replanting in major rubber and oil palm plantations, traditionally used for charcoal production. Since several existing plantations intend to expand their areas of operation, we assume an annual replanting rate, enabling steady availability of fuel. Projects are evaluated based on their Net Present Value (NPV) and marginal cost of connection. The electric grid is extended to districts with the highest NPV, thereby forming an electrical network.

We employ two decision strategies for the general operation of the model. In the first strategy, Power Plants aim to maximize the level of self-generation to satisfy the plantation's electricity demand while in the second they maximize the plantation's producing area. The first strategy results in lower investment costs, higher NPV and lower land requirement, with fewer unelectrified districts.

We find that less than 2% of a plantation's producing area is sufficient to support the networks over a period of 30 years. Residential power consumption patterns neither impact land use nor profitability due to large differences between industrial and residential load consumption patterns. An increase in annual demand growth rates has a negligible impact on the system. However, transmission line costs have a high effect on the electrification patterns.

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Contents

1. Introduction

This project uses an Agent-Based Modeling (ABM) to simulate the provision of electricity from woody biomass residues to rural residential districts in Liberia. The residues in consideration are obtained from replanting non-producing rubber and oil-palm plantations across the country.

Electricity is a luxurious commodity for Liberians. Prohibitive costs and a low access rate stem from a severely damaged infrastructure and heavy reliance on diesel. The Liberian government is collaborating with several international consultants to identify a sustainable energy pathway for the country. The National Renewable Energy Laboratory (NREL) estimates Liberia's biomass resources to be more than sufficient to support its annual electricity and oil consumption [2]. Decentralized power generation from these biomass resources is the cheapest way to satisfy the nation's rural residential demand till 2050, when compared with other renewable energy sources, diesel power and grid extension [3]. Utilizing plantation residues for generating power on-site is a simple way to overcome logistical issues associated with handling and transportation of the fuel. Case studies from South Asia and Sub-Saharan Africa consistently show that off-grid electricity supply from biomass sources generates employment opportunities and stimulates the local economy[4–7].

An ABM is the representation of a system defined by the interactions of its decision-making entities (or agents) amongst themselves in a specific environment. These agents are autonomous bodies that make decisions based on some criteria [8] and the environment provides the context in which agents interact [9]. The flexibility of ABM is its ability to capture emergent phenomena and provide a realistic representation of the system [8] making it an appropriate instrument to solve energy problems in developing countries today.

In the remainder of the thesis, we will introduce the reader to Liberia's energy and cash crop sectors. We will then describe the methods used to conduct our analysis, highlight key findings and discuss our results.

1.1 Liberia's Energy Sector

Primary energy uses: With a population of 4.5 million, approximately 90% of Liberians rely on traditional biomass for cooking and heating [10]. While some depend on firewood, a significant proportion of the population is heavily dependent on charcoal [11]. Imported petroleum products of major importance are gasoline and diesel fuel oil, while the country also imports jet fuel and kerosene. These are ultimately used for transportation, electricity and domestic lighting [10]. Rural households generally lack access to electricity, and mainly rely on oil lamps, flashlights and candles for lighting[6].

Renewable Energy Resource Potential: Liberia has an identified capacity of 967MW for large-hydro generation according to a project underway to set up a regional electricity market for the Economic Community of West African States (ECOWAS) [12]. Table 1 shows estimates of Liberia's renewable energy potential based on many published works.

Energy Source	**Estimated Potential**	**Units**	**Source/s**
Small Hydro Power (SHP)[a]	57.3 (1 – 30 MW)	MW	[13]
	86 (1 – 30 MW)	MW	[14]
	200 (< 10 MW)	MW	[10]
Solar PV	6.67	TWh per year	[12]
	4 - 6	$kWh/m^2/day$	[10], [15]
Biomass	459	MW	[12]
	26,923	GWh/year	[2]
	27,452	GWh per year	[10]
CSP, Wind	0	MW	[12]

Table 1. [a]The large variation small hydro potential indicates the need for an updated study on Liberia's SHP potential.

According to the International Renewable Energy Agency (IRENA), Liberia can support more than 75% of its electricity generation from its own renewable sources [16]. Several domestic renewable energy development projects are in the pipeline; however, serious institutional barriers such as lack of coordination between energy-related organizations and poor renewable energy data collection and analysis must be overcome so that the country may benefit from tapping its own resource potential.

The Electricity Sector: With one of the lowest access rates (1.2% rural, 18.9% urban [17]) and one of the highest tariffs ($0.52/kWh) in the world, most Liberians resort to informal power producers or self-generation to satisfy their electricity demand.

Prior to the civil wars of 1989-1996 and 1999-2003, Liberia's installed capacity of 412 MW powered an operational grid across Monrovia and several stand-alone systems in major towns. The mining and agricultural industries contributed to approximately half of this capacity [18]. In the aftermath of a fourteen-year civil conflict and the Ebola epidemic, Liberia seeks to rebuild its electricity sector as one of many endeavors to regain political and economic stability. Immediately following the second civil war, the government worked with foreign-aid organizations to build a small grid in Monrovia of 9.6MW, powered by high-speed diesel generators [19]. The only electric utility in Liberia, Liberia Electricity Corporation (LEC) was restored at this time. Presently, Liberia's power generation capacity stands at 38MW, its generation mix consisting of Heavy Fuel Oil and Diesel [16,20].

Evolution of Energy Policy: Energy policy in Liberia has been ambitious, and has thus far maintained its focus on being transformative. One of the first initiatives by the Government of Liberia (GoL) towards revitalizing its energy sector was the creation of the National Energy Policy in 2009, which set clear energy access targets for the country to achieve by 2015 [18].

This saw the creation of a renewable energy fund (REFUND) and the establishment of the Rural and Renewable Energy Agency (RREA). At the same time, Liberia also became a member of the ECOWAS community.

The management contract between LEC and Manitoba Hydro International (MHI) of 2010 was beneficial to the LEC with the creation of business strategies and short to medium-term plans to improve the efficiency of the company. However, the public utility plans to expand its services in Monrovia and surrounding areas and it will be a long time before the rest of Liberia is grid-connected. In order to overcome this time lag, several transmission infrastructure development projects are underway such as the Liberia Energy Access Project, Liberia Energy Sector Support Program, the Cote d'Iviore / Liberia / Sierra Leone / Guinea (CLSG) and cross-border electrification projects by the West African Power Pool (WAPP). Though these projects are primarily funded by international donor organizations, they have had difficulty in attracting private sector funding due to lack of regulation, lack of political will to introduce reforms and lack of institutional support [21].

Last year, the Liberian senate passed the 2015 Electricity Law of Liberia, which aims to make the power sector more attractive to private investors by establishing a legal and regulatory framework for power generation, transmission, distribution and retail. The law also requires the creation of an Independent Regulatory Commission, who will receive the responsibilities now held by the Ministry of Lands, Mines and Energy (MLME) [22]. The passage of this bill marks the beginning of the end of LEC's monopoly, since it encourages the emergence of Independent Power Producers (IPPs) and unbundling of the electricity sector through private investment. Although electricity policy is still in its infancy in Liberia, the country stands to gain by avoiding common pitfalls like regulatory capture.

Although more than 90% of Liberians are heavily reliant on charcoal and woodfuel, the charcoal industry remains mostly informal and unregulated. Currently, international donor organizations and the government are focusing primarily on providing access to modern energy services. However, there is little attention on how to ensure a smooth transition from use of charcoal to these new services. Jones [23] emphasizes the need for decision-makers to shy away from assuming that Liberians will transcend the traditional energy ladder, when the use of charcoal is deep-rooted in the people's culture and lifestyle. Instead, he encourages decision-makers to create an institutional, legal and technological framework for the regulated operation of one of Liberia's most profitable, environmentally damaging industries that provides employment to numerous Liberians.

1.2 Rubber and Oil-palm plantations in Liberia

With an aggregate production area of 100,000 hectares, Liberia is a major producer and exporter of natural rubber in the African continent [24]. Since oil-palm is strategically bred for export, several large scale government-owned oil-palm plantations were established all over the country in the 1980s. Both industries are key components of the agricultural sector, which employs more than 70% of the population [25]. Most of these plantations were abandoned or destroyed during the civil conflict, and are now under rehabilitation. Due to a sharp decline in commodity prices and reduced productivity from aged trees, major plantation companies have tremendously cut back on production [26]. Consequently, this has severely impacted the country's workforce and earnings from exports. Natural rubber exports decreased from 36.9% of total exports in 2012 to 17.5% in 2014 [27,28]. Several foreign rubber and oil-palm companies own and operate industrial plantations in the country. The GoL signed concession agreements with these companies, allowing them to expand their operations onto much larger areas of land.

Table 2 outlines the results of a desk study of bio-power availability from Liberia's major rubber and oil palm plantation companies. Although a significant proportion of national production is from smallholder farmers and companies continue to purchase harvest from them, their policies of working with smallholders in the future is unclear. It is expected that once companies begin to profit from replanting, they may compete with smallholder farmers rather than working with them [29]. The use of residues for power generation is an opportunity to create domestic value in a country that is highly export-dependent. We expect this socio-economic system to foster a symbiosis between the charcoal industry, smallholder farmers, plantation companies, the state utility, IPPs and electricity distribution companies. In the next chapter, we describe the ABM used to simulate this energy system.

Plantation	**County**	**Ownership**	**Crop**	**Total Area (hectares)**	**Producing Area (hectares)**
Firestone	Margibi	Bridgestone	Rubber	47753	25000
Liberian Agricultural Company (LAC)	Grand Bassa	SOCFIN	Rubber	22000	9500
Guthrie	Bomi	Sime Darby	Rubber	121406	8907
Senjeh	Bomi	Sime Darby	Rubber	12661	107
Cavalla	Maryland	SIPH	Rubber	35000	5630
The Cocopa Plantation	Nimba	The Liberia Company (LIBCO)	Rubber	10117	3441
Salala Rubber Plantation	Margibi	Salala Rubber Corporation, SOCFIN	Rubber	8500	4777

Plantation	**County**	**Ownership**	**Crop**	**Total Area (hectares)**	**Producing Area (hectares)**
Sinoe Rubber Corporation	Sinoe	Mesurado Group	Rubber	242812	20243
Morris American Rubber Company	Montserrado	Liberian-owned	Rubber	4047	2429
Foya	Lofa	GoL	Oil-Palm		2300
Kpatawee	Bong	GoL	Oil-Palm		560
Zleh Town	Grand Gedeh	GoL	Oil-Palm		830
Dubwe	Grand Gedeh	GoL	Oil-Palm		1214
Fendell	Bong	GoL	Oil-palm		70
Mount Coffee	Grand Bassa	GoL	Oil-palm	13961	5600
Matambo Estate	Grand cape Mount	Sime Darby	Oil-palm	15000	2868
Cape Mount Estate	Grand Cape Mount	Sime Darby	Oil-palm		1992
Bomi Estate	Bomi	Sime Darby	Oil-palm	10000	3179
Lofa Estate	Bomi	Sime Darby	Oil-palm		1996
Palm Bay Estate	Grand Bassa	Equatorial Palm Oil (EPO)	Oil-palm	13007	5600

Plantation	**County**	**Ownership**	**Crop**	**Total Area (hectares)**	**Producing Area (hectares)**
Butaw Estate	Sinoe	EPO	Oil-palm	8011	1700
Golden Veroleum (GVL) Estates	Sinoe	GVL	Oil-palm	12000	2530
GVL Estates	Sinoe	GVL	Oil-palm	8000	600
Maryland Oil Palm Plantation	Maryland	SIFCA	Oil-palm	15000	9000

Table 2. Sources: [15,30–45].

Note: This list is not exhaustive, and is indicative of the plantations considered in our ABM. Information on the GoL-owned oil-palm plantations is not readily available, hence the total area is difficult to estimate.

2. Methods

Two geo-spatial tools for planning rural electrification are extremely relevant to this study. The NetworkPlanner tool developed by the Sustainable Engineering Lab at Columbia University (networkplanner.modilabs.org) compares the costs of different power generating technologies and grid architectures. While it provides great flexibility in using a variety of demand and transmission infrastructure datasets, its consideration of electricity technologies is limited to solar and diesel. Its powerful network-planning algorithm develops the least-cost electrical network that is partially built by extending the existing grid, and also consists of standalone systems and microgrids.

The Reference Electrification Model (REM), developed by MIT’s Universal Energy Access Research Group, is a sophisticated version of NetworkPlanner. It considers a consumer’s location, electrification status and type [46] and designs an optimized grid structure based on technical and economic specifications. As with NetworkPlanner, it considers only solar and diesel options for power generation.

Modeling the use of biomass residues for power generation is uniquely complicated in that, biomass availability, fuel quality, costs of transportation and handling must be taken into account. Buchholz et al. [47] illustrates these calculations by simulating the use of residues from short-rotation woody crops for combined heat and power in Uganda.

ABM is the ideal tool to analyze this energy system as compared to a traditional optimization model or an endogenous technological change model [48] since we are dealing with a complex system. Many variables such as the biomass stock, fuel prices, load consumption pattern and the structure of the grid itself are in a constant state of flux, so it is key to use a modeling technique that provides insight into “what could be.” The objective is not to control the energy system, instead to understand what it could look like in different scenarios, and to guide further analysis that will aid in better understanding of this system.

Our ABM incorporates the geo-spatial aspects of consumer demand data and flexibility in grid structure from NetworkPlanner and REM. Although our model assumes power generation at the plantations’ sites to minimize handling and transportation costs, the user can consider siting power plants away from the plantations by developing an algorithm based on Buchholtz et al. [47].

We chose NetLogo due to several reasons. On one hand, its flexibility in managing datasets and customizing source code allows the decision-maker to specify details in our model with greater ease. Netlogo’s language and user-friendliness allows the user to refine the model by adding agents and modify their decision-making processes. Scenarios and algorithms can be easily altered to suit the decision-maker’s criteria. Required inputs can also be modified according to data availability. As long as the underlying logic is based on a strong empirical foundation, the results of the ABM will be reliable.

2.1 Model Overview

We seek to answer the following questions using the ABM:

- Is it economically feasible to use the biomass residues available at cash crop plantations to satisfy rural residential electricity demand?
- What percentage of plantation area is required to sustain power production?
- What percentage of the population’s electrical demand is satisfied?
- What is the resulting total installed capacity?
- What is the required initial investment?

This model is based on previous work by Alfaro et al. [49], which aims to promote the use of ABM as a tool for renewable energy planning in developing countries. The authors develop a strategy to choose from available renewable energy sources for rural electrification using the Levelized Cost of Electricity metric (LCOE).

This model calculates the optimal sequence of extending the grid from biomass power plants to Demand Centers (DCs) based on the marginal cost of the connection and the NPV of the project. Embedded in these metrics are the associated costs and anticipated revenues over the lifetime of the project. The model was constructed using NetLogo (v5.2.0)[1] with use of the GIS and Network Extensions.

Data and Sources: The construction of political boundaries and rural district population information is based on data from the Liberia Institute of Statistics and Geo-Information Services (LISGIS) [49]. Residential DCs are placed at the geometric center of each district boundary. Each plantation is associated with a resource potential as well as an industrial load profile. The resource potential at each plantation is estimated according to an annual replanting rate as shown in Table 3, while their locations were approximated using map data from Google [50–73]. Load consumption patterns for residents and industries, technology and infrastructure costs were assumed with reference to energy planning reports in Liberia and the West African region [3,10,12,74–76]. Power Plants are located at the plantation site. This minimizes the cost of transportation and handling of residues and the cost of distribution of electricity back to the plant. As a result, these costs are considered negligible in our model. Figure 1 is a snapshot of the model after loading the DCs.

Plantation	**Resource potential**		
	Replant 100% producing area (GWh)	**Replant 2% producing area per year (GWh/year)**	**Replant 5% producing area per year (GWh/year)**
Firestone	3038	61	152
Liberian Agricultural Company (LAC)	1154	23	58
Guthrie	1082	22	54
Senjeh	13	0.26	1
Cavalla	684	14	34
The Cocopa Plantation	418	8	21
Salala Rubber Plantation	580	12	29

Sinoe Rubber Corporation	2460	49	123
Morris American Rubber Company	295	6	15
Foya	276	6	14
Plantation	**Resource potential**		
	Replant 100% producing area (GWh)	**Replant 2% producing area per year (GWh/year)**	**Replant 5% producing area per year (GWh/year)**
Kpatawee	67	1	3
Zleh Town	100	2	5
Dubwe	146	3	7
Fendell	8	0.17	0.42
Mount Coffee	672	13	34
Matambo Estate	344	7	17
Cape Mount Estate	239	5	12
Bomi Estate	381	8	19
Lofa Estate	240	5	12
Palm Bay Estate	672	13	34
Butaw Estate	204	4	10
Golden Veroleum (GVL) Estates	304	6	15
GVL Estates	72	1	4
Maryland Oil Palm Plantation	1080	22	54

Table 3. Yields of dry woody biomass from replanting for rubber and oil-palm are 81 and 80 dry tonnes per hectare respectively, thermal efficiency is 1.5 MWhe per dry tonne of biomass [2]. Note: Producing area is shown in Table 2.

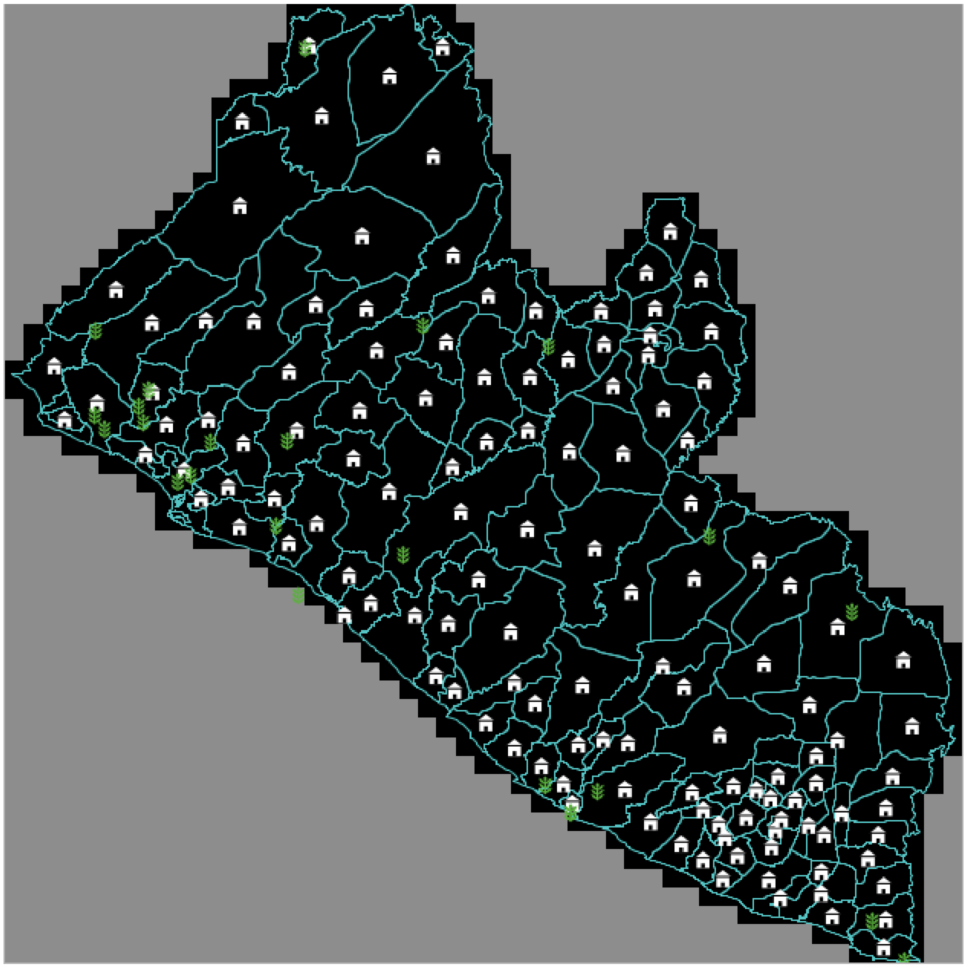


Figure 1. The Netlogo world. Black patches make up the country of Liberia. Cyan lines represent district boundaries, which are drawn with the help of the Netlogo GIS Extension and GIS datasets provided by LISGIS. Residential districts are represented by white houses, and plantations by green plants. We disregard Monrovia and the county Montserrado, since it is predominantly urban and contains the national grid. This space can be re-modelled for any region as long as GIS data is available.

2.2 Agent-Based Modelling

We describe our model using a top-down approach. First, we introduce the roles and objectives of agents in decreasing order of importance. Next, we describe the environment in which the agents interact and delve into the decision strategies employed in the model. Finally, we explain the scenarios created by changing model parameters.

Agents: The **Observer** sets the values of variables, chooses a decision-strategy to employ and runs the simulation. Table 4 lists the key parameters that the Observer needs to specify for the model to yield different outcomes. It also includes our assumptions that form the basis for the results of this work.

Consumer Demand Pattern		
Residential Peak Load (W/household)	130	[75]
Average Plantation Load Factor	0.43	[12]
Plantation Peak Load (W/planted hectare)	200	[15,34,77]
Average Residential Load Factor	0.375	[12]
Annual Demand Growth Rate (%)	2	Assumed
Plantation Variables		
Observer-defined Replanting rate (% planted area)[a]	2	Assumed
Average yield of biomass residue (dry tonnes/hectare)	80.5	[2]
Lower Heating Value (GJ/tonne)	19	[76]
Powerplant Variables		
Capital Cost ($/kW)	3600	[74]
Fixed Operations and Maintenance (O&M) Costs ($/kW-year)	162	[74]
Variable O&M ($/MWh)	4	[74]
Fuel Cost ($/ton)	16	[74]
Heat Rate (GJ/MWh)	9.47	[12]
Lifespan (years)	30	[12]
Construction time (years)	4	[12]
Capital spent in the first year of construction	50%	[12]
Economic Variables		
Discount Rate	10%	Assumed
Fuel price inflation rate	1%	[6]
Electricity Tariff ($/kWh)	0.3	[6]

Table 4. [a]Observer-defined Replanting rate needs to be specified when using the Maximum Area Utilization strategy only.

District agents are located at the centroid of each district boundary. They are also DCs whose demand is estimated based on the local population. **Darks** are Districts waiting to be electrified while **Incompletes** have been electrified but a portion of their demand is unsatisfied. At the time of loading the world, all Districts are Darks. Each Dark aims to be chosen by a supplier to have its demand completely satisfied. An **Electrified** is a District whose demand has been completely satisfied. Once they become nodes in a microgrid, Electrifieds search for the ideal agent to whom the grid will be extended at every iteration. **Unmets** are Districts that have not been electrified at the end of the simulation.

The **Plantation** agent supplies Powerplants with biomass residues. They are DCs whose demand is calculated from the producing area, and the biomass potential is approximated using a user-specified percentage of producing area that will be replanted every year. Plantations, like Districts, connect to Powerplants to satisfy their demand. Once satisfied, Plantations also search for the most profitable DC to whom the grid will be extended, depending on the available power capacity of their supplier.

The **Powerplants** generate electricity from residues supplied by the Plantations. They are located on the same patch as the Plantations to minimize costs of handling and transportation of fuel as well as distribution costs. They function as suppliers of their electrical networks. All Powerplants store the load profiles of their consumers and calculate the NPV of their operations at every iteration. Powerplants aim to utilize their power producing capacity by extending the electrical network to agents who increase their NPV.

Links are built between agents that are part of an electrical network. A link does not make decisions, but aids agents connected to it to identify as part of the same microgrid. They behave similar to transmission lines, and assume the properties of 33kv low voltage transmission lines used for rural electrification infrastructure projects in Africa.

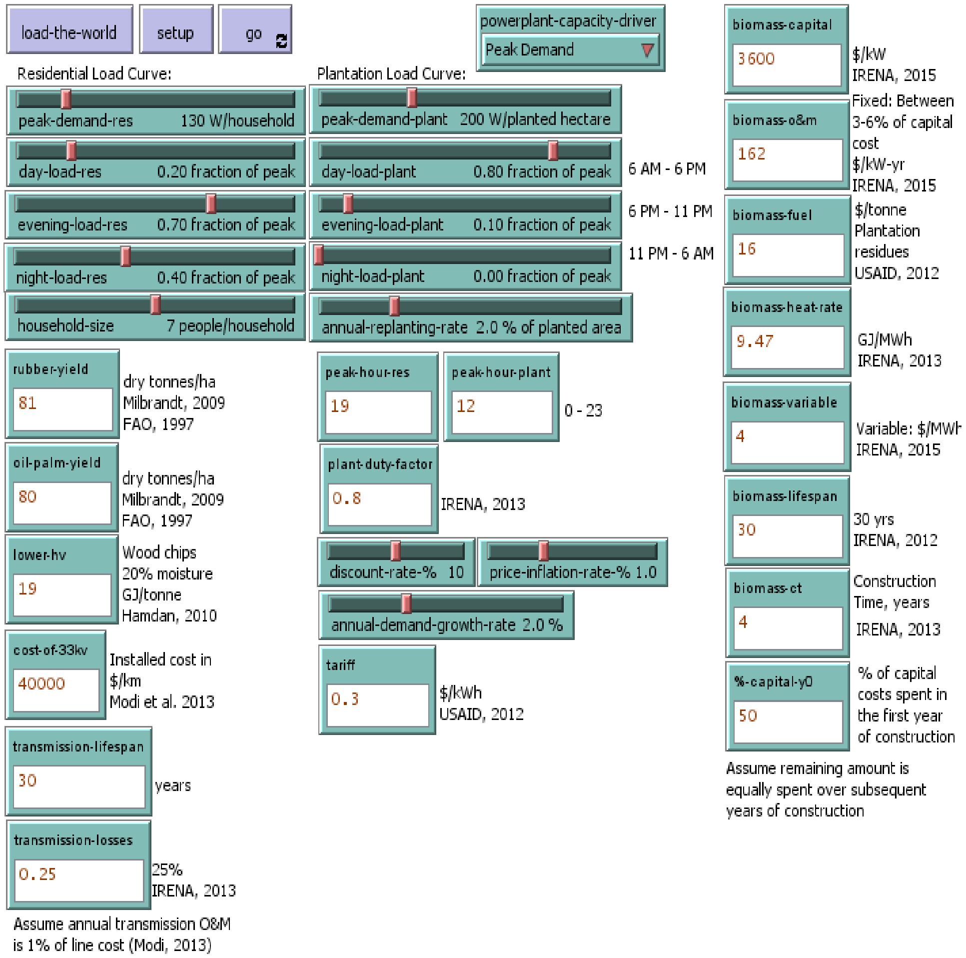
The **Patches** make up the Netlogo world. They also do not make decisions; rather they aid other agents in accessing geographic data. Those that belong to the country of Liberia hold the names of the district and county as attributes.

Environment The simulation is run in three parts. First, the Observer sets parameters and loads the world. At this point, the GIS dataset is loaded and the DCs are formed. Patches are associated with a county and district. Districts (now all Darks) have a population, and Plantations are associated with total and planted areas. While all agents own agent-specific variables, they can also access global variables in the program. These variables are part of the world, and are set by the Observer prior to starting the simulation. Figure 2 shows the parameters that the Observer needs to set prior to setting up the system.

Decision Strategies: Two strategies determine the way Powerplants are sized. In the Satisfying Plantation Demand (SPD) strategy, the plant is sized based on the plantation demand. Each DC has a 24-hour load profile. When the Powerplant connects to a Plantation, it sets its capacity to the maximum hourly load in that profile. As more agents join the Powerplant's network, it revises its capacity to the maximum aggregate demand of connected projects. Figure 3 illustrates the SPD strategy when a Powerplant is connected to one Plantation and one District. It is worth noting the disparity between residential and industrial load profiles.

In the Maximum Area Utilization (MAU) strategy, Powerplants are sized to the maximum residues available from re-planting a percentage of the plantation's producing area. This potential is estimated as shown in Table 3. The Observer-defined Replanting rate (OR) is the most important variable in this strategy, since Powerplants cannot revise their capacity once it is set. A very low value may leave insufficient capacity to electrify other districts, and a very high value may cause revenue loss. The significance of this variable is further explained in the Results section. The installed capacity is given by the following equation:

$$Installed\ Capacity\ = \frac{Yield \times OR \times Producing\ Area \times LHV}{Heat\ Rate \times Min\ (Duty\ Factor, Load\ Factor)}$$



powerplant-capacity-driver: Peak Demand

Residential Load Curve:

peak-demand-res 130 W/household

day-load-res 0.20 fraction of peak

evening-load-res 0.70 fraction of peak

night-load-res 0.40 fraction of peak

household-size 7 people/household

Plantation Load Curve:

peak-demand-plant 200 W/planted hectare

day-load-plant 0.80 fraction of peak — 6 AM - 6 PM

evening-load-plant 0.10 fraction of peak — 6 PM - 11 PM

night-load-plant 0.00 fraction of peak — 11 PM - 6 AM

annual-replanting-rate 2.0 % of planted area

rubber-yield: 81 — dry tonnes/ha Milbrandt, 2009 FAO, 1997

oil-palm-yield: 80 — dry tonnes/ha Milbrandt, 2009 FAO, 1997

lower-hv: 19 — Wood chips 20% moisture GJ/tonne Hamdan, 2010

cost-of-33kv: 40000 — Installed cost in $/km Modi et al. 2013

transmission-lifespan: 30 — years

transmission-losses: 0.25 — 25% IRENA, 2013

Assume annual transmission O&M is 1% of line cost (Modi, 2013)

peak-hour-res: 19

peak-hour-plant: 12 — 0 - 23

plant-duty-factor: 0.8 — IRENA, 2013

discount-rate-% 10

price-inflation-rate-% 1.0

annual-demand-growth-rate 2.0 %

tariff: 0.3 — $/kWh USAID, 2012

biomass-capital: 3600 — $/kW IRENA, 2015

biomass-o&m: 162 — Fixed: Between 3-6% of capital cost $/kW-yr IRENA, 2015

biomass-fuel: 16 — $/tonne Plantation residues USAID, 2012

biomass-heat-rate: 9.47 — GJ/MWh IRENA, 2013

biomass-variable: 4 — Variable: $/MW IRENA, 2015

biomass-lifespan: 30 — 30 yrs IRENA, 2012

biomass-ct: 4 — Construction Time, years IRENA, 2013

%-capital-y0: 50 — % of capital costs spent in the first year of construction

Assume remaining amount is equally spent over subsequent years of construction

Figure 2. The Observer specifies parameters listed in Table 4 using NetLogo.

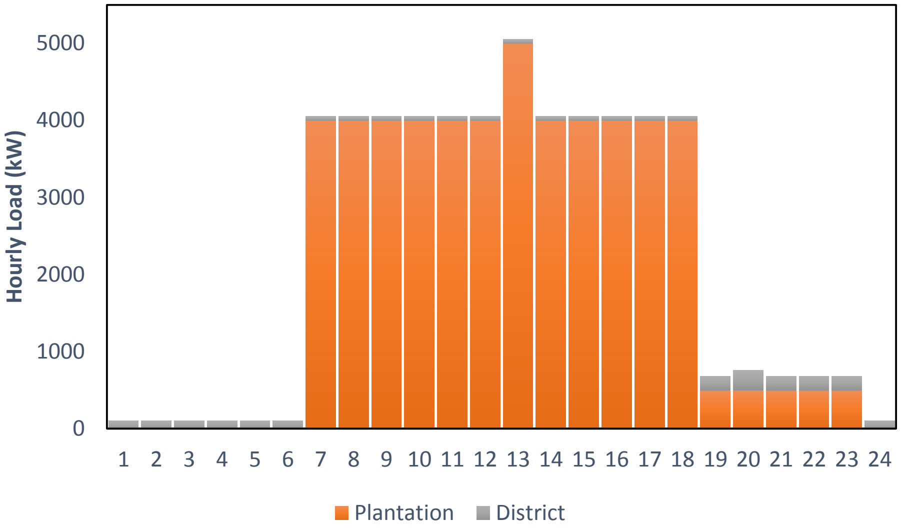


Figure 3. Sample Load Profile: Powerplant

Powerplants are built next to every Plantation and links are formed between them, creating the first links of a microgrid network. At every iteration, all Powerplants not fully utilizing their capacities indicate to their networks that they are available. Agents in the network shortlist DCs based on transmission constraints. All shortlisted DCs then calculate the NPV and the Marginal Cost (MC) of connecting to the nearest available agent in these networks. The network agents order eligible DCs in decreasing order of NPV. The DC with the highest NPV is chosen and connected to. In the case of similar NPVs, the agent with lower MC is chosen. The Powerplants then sum the load curves of connected projects, reset their capacity if necessary, and calculate NPV and LCOE.

Another crucial metric calculated by Powerplants at every iteration is the Required Replanting rate (RR). This is calculated when both strategies are employed. RR represents the percentage of the plantation's producing area that needs to be replanted every year in order to ensure steady availability of fuel over the lifetime of the project.

Scenario Building: We designed our experiments to determine the effect of residential consumer demand patterns and transmission infrastructure cost on profitability, fuel stability and grid structure. In the MAU strategy, we explore the effect of OR (therefore the installed capacity of Powerplants) on the system. Our measures for profitability are the LCOE and NPV. RR is our measure for fuel stability. We track the number of Incompletes, Unmets and microgrids formed at the end of each simulation to conceptualize the structure of the grid.

Scenarios are built through one-at-a-time variation of residential peak load, annual demand growth rate, residential day load, transmission line cost, discount rate and OR (Table 5).

Strategy	**Residential Peak Load (W/household)**	**Residential Day Load (fraction of peak)**	**Annual Demand Growth Rate (%)**	**OR (% producing area)**	**Cost of transmission line ($/km)**	**Discount Rate (%)**
SPD	110	0.2	0.5	1	40,000	8
MAU	130	0.3	2	2	80,000	10
	150	0.4	5	3	120,000	12
		0.5		4		

Table 5.

2.3 Net Present Value and Levelized Cost of Electricity

In the model, Districts and Powerplants calculate their NPV over their lifetime of n years using the following formula:

$$NPV = \sum_{i=0}^{n} Revenues - \sum_{i=0}^{n} Fixed\ Costs - \sum_{i=0}^{n} Variable\ Costs$$

$$Revenue_i = Tariff_i \times Annual\ Generation_i$$

$$Annual\ Generation_i = \sum_{j=1}^{24} Load_{ji} \times 365$$

$$Load_{i+1} = Load_i \times (1\ + dgr)^{i+1}$$

$$Variable\ Costs_i = F_i + VOM_i$$

$$F_{i+1} = \ F_i\ (1\ + pin)^{i+1}$$

$Load_j$ represents load in hour j, dgr is the annual demand growth rate. F_i, and VOM_i represent the fuel and Variable O&M costs in year i respectively. pin is the annual price inflation rate.

Fixed costs are different for each type of agent. For Districts, the annual costs are calculated so that each District pays the additional operating cost to the Powerplants towards satisfying its demand. Each District also pays costs to install and maintain the transmission line for extending the grid towards it. Due to limited availability of data, the transmission costs in this model are purely line costs and do not include transformer or distribution costs.

At i = 0,

$$Fixed\ Costs_0 = Transmission\ Capital$$

At i > 0,

$$Fixed\ Costs_i = TOM_i$$

TOM_i represents the transmission O&M costs in year i.

Powerplants calculate their annual costs at the beginning of every iteration. For the sake of distributing capital costs over the construction period, we assume that a portion of the total Capital Cost is paid in year 0. Then the Powerplants pay an instalment each year until the end of the construction period, along with interest on the amount due.

At i = 0,

$$Fixed\ Costs_0 = Cap_0$$

While i > 0 and i <= k - 1,

$$Fixed\ Costs_i = Cap_i + d \times \sum_{j=i}^{k-1} Cap_j$$

Cap_i represents the installment of Capital Costs in year i over a construction period of k years. d represents the discount rate.

At i >= k,

$$Fixed\ Costs_i = FOM_i$$

FOM_i represents the fixed O&M costs in year i.

The calculation of LCOE for Powerplants and Marginal Cost for DCs is adapted from the formula recommended by IRENA [78]. Notations are consistent with those defined earlier.

$$LCOE = \frac{\sum_{i=0}^{n} \frac{Fixed\ Costs_i + Variable\ Costs_i}{(1+d)^i}}{\sum_{i=0}^{n} \frac{Annual\ Generation_i}{(1+d)^i}}$$

2.4 Verification

The process of verification is done to ensure that the model is behaving as it was intended. While building the model, we tracked the behavior of random individual agents whenever changes to an agent's decision strategies were made. Many of these verifications were visual, by continuously using the 'View Updates' feature in NetLogo as the model progressed. We also printed outputs for random individual agents at different stages of the model's construction to ensure that there were no bugs in the code. Wherever applicable, we tested the sensitivity of outputs to changing inputs and compared them with separately computed values. Once the model was complete, individual Powerplant outputs were printed for all the scenarios listed in Table 5. These outputs were found to be consistent with theoretical expectations.

2.5 Validation

Validation is confirmation that the model approaches reality. Data inputs to this model were gathered from research either in Liberia or in the West African region, and closely reflect present-day values. Since the intention of this model is to create informed choices for an energy system that does not exist, it is not possible to compare its outputs with the real-world. Validation through historical backcasting is also not applicable. Hence, we seek to validate the model through subject matter experts by engaging multiple stakeholders such as the RREA, LEC and plantation companies. Their evaluation of the model will ensure its validity. Next, we aim to validate this model by comparing its results with an already validated model like the NetworkPlanner tool. Alternatively, we would validate it against a replica which models the system using a different methodology such as System Dynamics. Finally, depending on the resources available to us, we would seek to build a prototype microgrid to check if our representation of the system captures important relationships and patterns in reality.

3. Results

3.1 Observer-specified Replanting Rate

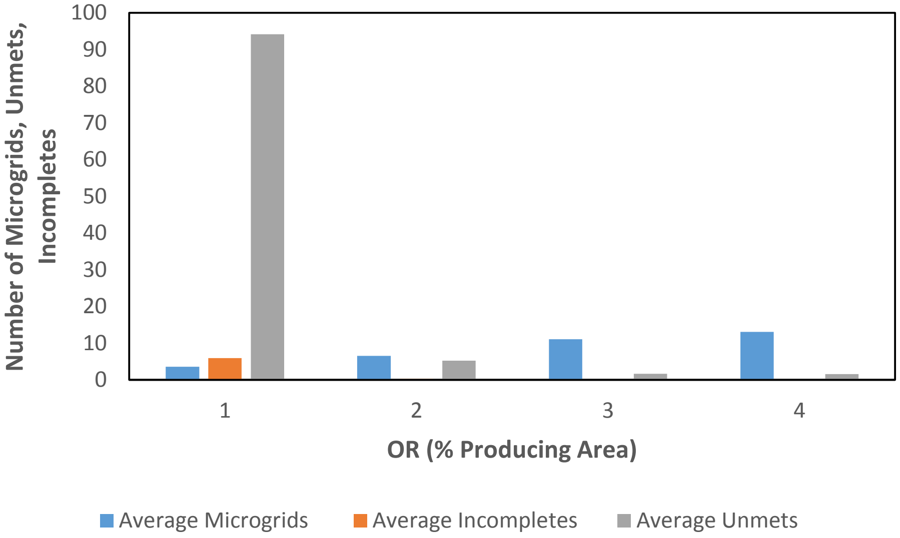


Figure 4. Effect of OR on Grid Structure

On average, approximately 94 districts (out of 134) are left unelectrified at a low OR of 1% due to insufficient or unsuitably located capacity. The contribution of transmission costs to the total costs varies from 10% to 5%, while overnight capital costs rapidly increase by 300% as OR increases (Figure 5). The NPV of the system dips due to high capital costs that are not recovered over the lifetime of the project, while more Powerplants gain the capacity to support microgrids. Since producing area varies widely across plantations, a higher OR would make Powerplants attached to smaller plantations capable of powering more districts, whereas those supplied by larger plantations would operate in loss because of a low load factor. To provide a more useful insight into the behavior of the system, we analyze further results of the model using OR values of 2% and 3% only.

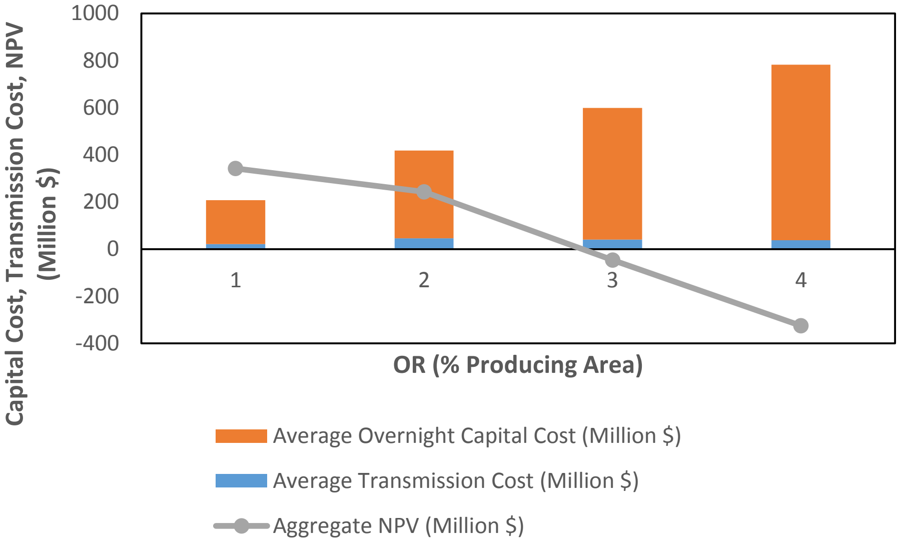


Figure 5. Effect of OR on Profitability

3.2 Residential Demand Profile

Day Load (6AM to 6PM): There is a significant difference in the average LCOE resulting from the two strategies (Figure 6). The LCOE in the MAU strategy fluctuates from $0.3/kWh to $0.35/kWh, while the range is much lower for the SPD strategy from $0.13/kWh to $0.15/kWh. The day load, input as a percentage of the peak load, is gradually increased in steps of 10 percentage points from 20% to 50% of the peak. The decrease in LCOE with the increase in day load indicates that Powerplants see a substantial benefit when there is increased usage of power generation during the day. Interestingly, the steeper slope in the MAU strategy shows that these Powerplants have a larger capacity and a lower load factor. As expected with decreasing LCOE, the aggregate NPV of all Powerplants averaged across simulations is seen to increase (Figure 7). NPV in the MAU strategy is significantly lower than the SPC strategy, and rises sharper with increase in day load.

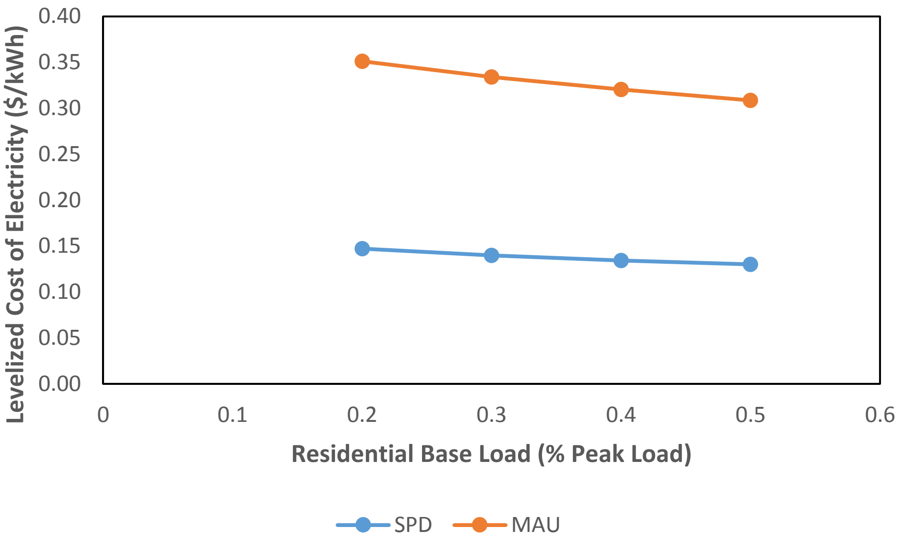


Figure 6. Effect of Residential Base Load on LCOE

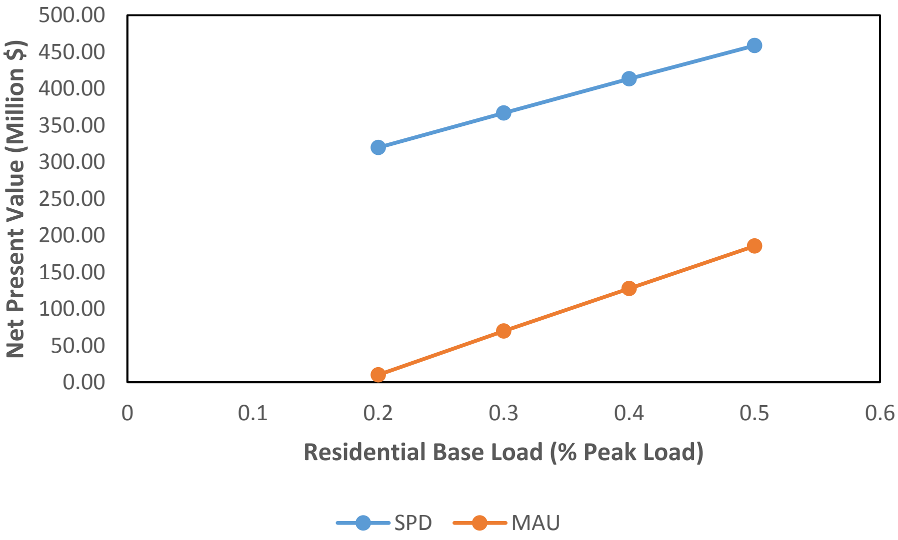


Figure 7. Effect of Residential Base Load on NPV

Residential Peak Load: We varied peak demand per household from 110W to 150W in intervals of 20W. In the SPD strategy, there was a marginal increase in LCOE as peak load increased (Figure 7, $0.1376/kWh to $0.1382/kWh) while NPV saw a significant increase (Figure 8). The higher LCOE may be attributed to slightly greater fixed costs, since Powerplants size their capacity according to the maximum hourly demand in their network (Section 2.2).

Increasing NPV indicates that the annual revenue to Powerplants from increased sales of electricity is much greater than the increase in the annual costs. In the MAU strategy, the results are similar to those with increasing day load; decreasingCOE and an increasing NPV. The difference in slopes between these points hints at a non-linear relationship between household peak load and profitability, which may be a worthwhile investigation in the future.

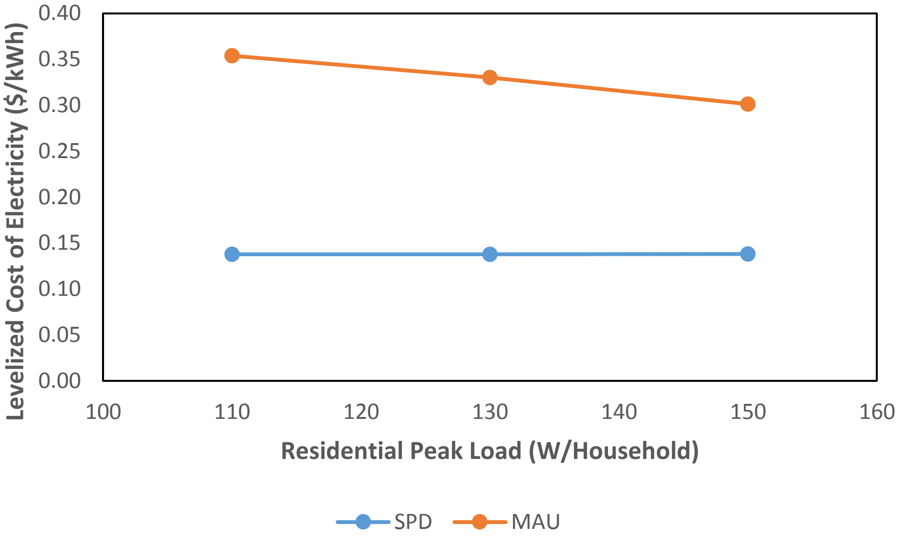


Figure 8. Effect of Residential Peak Load on LCOE

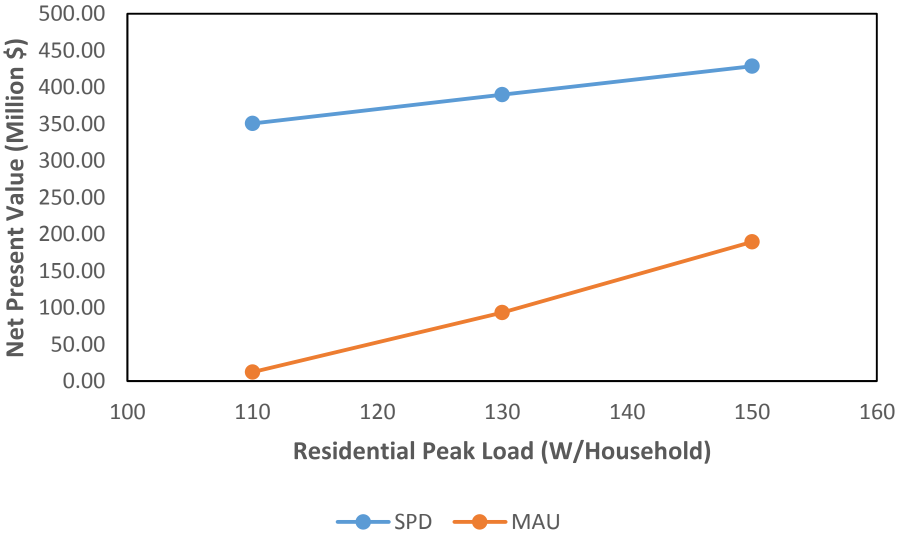


Figure 9. Effect of Residential Peak Load on NPV

Increase in residential consumption yielded numerically similar results for RR. In all 14 cases, RR was consistently lower than 1.8% of the Plantation's producing area. However, it is key to remember that this number represents the average RR among all Plantations, and it is very likely that smaller Plantations will need to replant a slightly higher percentage of their producing area every year. The consistent difference between RRs from the two strategies may be attributed to the variation in the size and shape of microgrids.

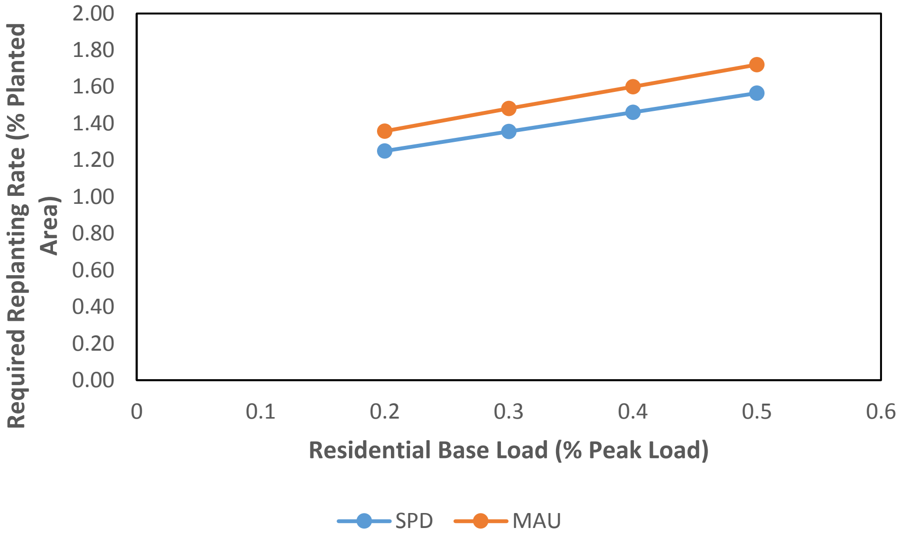


Figure 10. Effect of Residential Base Load on RR

3.3 Transmission Infrastructure Cost

The transmission infrastructure cost considered in the model is only the line cost, we do not include transformer or distribution costs. The relationship between the number of districts electrified and transmission line cost is clearly non-linear (Figure 11). As the line cost approaches $120,000/km, Powerplants find fewer viable districts to connect with. As many as 8 districts are unelectrified in the MAU strategy, whereas 3 districts are not connected to the grid in the SPD strategy.

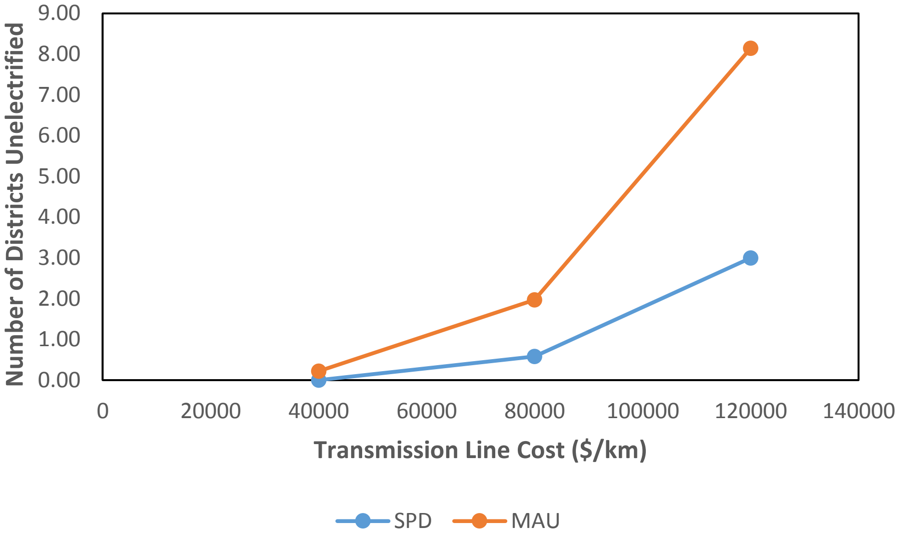


Figure 11. Effect of Line Cost on Unelectrified Populations

4. Discussion

Buchanan Renewables Energy (BRE) has previously attempted to use non-productive trees from rubber plantations for biofuel and power production in Liberia, shortly after the end of the civil conflict. Poor regulation, lack of transparency in the concession agreements and the government's inability to protect the rights of smallholder farmers and workers in the charcoal industry are some of the major reasons for BRE's lack of success [79,80].

Rubber, oil-palm and rice are agricultural resources that attract extractive investment in Liberia. Though well-intentioned, the concession agreements have not lead to the anticipated consequences of increased employment generation, a skilled labor force and a stabilized economy. The Liberian government is unhappy with the continued lack of indigenous production and extractive nature of commodity export, and intends to review the concession agreements in the near future [81]. Currently, oil-palm and rubber plantation companies can operate on 620,000 hectares and 370,000 hectares respectively over the next 45 - 60 years [82]. Most of this land has not yet been planted with oil-palm and rubber, contains sites of ecological and cultural importance, and is home to indigenous tribes.

The negative impacts of industrial plantation companies on the lives of the local people in Asia and Africa are well documented [24][83]. Major plantation companies in Liberia are not alone in violating human rights on accounts of slave labor, terrible working conditions and persecution of indigenous people to surrender their lands [84]. Like many of their international counterparts, they have also been guilty of causing severe environmental damage through monoculture cropping, deforestation and habitat destruction. In addition, they have had a troubling history of encroaching indigenous property and destroying cultural heritage sites[85].

There are many ongoing attempts to effectively regulate industrial plantation companies. The Roundtable on Sustainable Palm Oil (RSPO) is one such initiative, where members develop country-specific principles and practices for sustainable oil-palm production in the local context [86]. RSPO members range from plantation companies to banks and civil societies. One of many relevant Liberian laws is the Environmental Protection and Management Law of 2002, which mandates that all activities that will significantly impact the environment must undergo an Environmental Impact Assessment (EIA)[76]. The guidelines to conduct these assessments are prepared by the Liberian Environmental Protection Agency (EPA). According to the RSPO, plantation companies are required to conduct and make publicly available, an Environmental and Social Impact Assessment (ESIA) as well as a High Conservation Value (HCV) assessment. Companies operating in the extractive industry are required to comply with the procedures of the Liberia Extractive Industries Transparency Initiative (LEITI), an agency dedicated to transparent management of extractive industries in the country [87]. We anticipate that the decision makers listed in Table 6 will be instrumental in establishing and sustaining this bio energy system.

Name	**Specific Objective**	**Level of Jurisdiction**
ECOWAS Center for Renewable Energy and Energy Efficiency (ECREE)	Overcome barriers and create favorable conditions for regional renewable energy and energy efficiency markets across ECOWAS member states.	International
West African Power Pool (WAPP)	Promote and develop power generation and transmission infrastructure, set up a regional electricity market across ECOWAS member states.	International
Ministry of Lands, Mines and Energy (MLME)	Coordinate with development partners to oversee the development of energy projects and ensure their compliance with current policies and legislation. Regulate the functioning of LEC.	National
Rural and Renewable Energy Agency (RREA)	Work with communities to provide affordable electricity to off-grid, rural areas through low-carbon pathways using a dedicated public fund for renewable energy.	National
Liberia Electricity Corporation (LEC)[a]	Extend the grid across Monrovia and its surrounding areas, and ensure grid reliability. Engage in power generation, Transmission and Distribution (T&D) and retail of electricity.	Monrovia[b]
Name	**Specific Objective**	**Level of Jurisdiction**
Forest Development Authority (FDA)	Regulate and manage commercial forestry, community forestry and conservation forestry in Liberia.	National
National Bureau of Concessions	Monitors and manages legal and financial aspects of concessions in Liebria	National

National Charcoal Union of Liberia (NACUL)	Build capacity within the charcoal industry.	Monrovia and surrounding areas
National Oil Company (NOCAL) and Liberia Petroleum Refining Company (LPRC)	Administer and regulate the upstream and downstream petroleum sector according to policies and legislations set by MLME.	National
The World Bank, USAID, African Development Bank, Norwegian Agency for Development Corporation	Work with government agencies in Liberia to develop and implement energy access projects. Support these projects through financial and technological aid.	International

Table 6. Developed with reference to [76], which describes the involvement of government organizations in greater detail.

[a] In 2010, LEC signed a management contract with Manitoba Hydro International (MHI), allowing the Canadian firm to take over its business operations and develop strategies to ensure the utility's efficient performance over the next five years[88]. LEC plans to enter into another strategic partnership with MHI soon.

[b] Since LEC is the only utility in the country and it is publicly funded, its jurisdiction is limited to the extent of the national grid, which currently exists in Monrovia.

5. Conclusion

The results of our ABM indicate that change in residential power consumption patterns would not significantly impact land use. An increase in residential power consumption would simply make the power generation more effective, and is favorable to the power plants. Less than 2% of a plantation's producing area is sufficient to support this system over a project lifetime of 30 years. We found that an increase in annual demand growth rates had a negligible impact on the system, while the impact of transmission line cost was significant. As a result of huge disparities between industrial and residential load consumption patterns, the SPD strategy resulted in lower investment costs, higher NPV and lower RR, with fewer unelectrified districts. It is important to remember that this model is a simplistic representation of the grid, and is not indicative of actual power flows.

To effectively implement this model and ensure that this system sustains itself, it is essential to establish a decentralized power structure early on. IPPs will need to collaborate with the plantation companies and charcoal producers in order to procure fuel without drastically altering the informal, yet vital economy and severely impacting the environment. The Forest Development Authority can halt illegal expansions by the plantation companies into forests. It would be prudent for them to approve of the Environment and Social Impact Assessment as well as the High Conservation Value Assessment, in addition to the RSPO. T&D infrastructure costs cannot be handled by the power producers since they cannot control power flow. The Liberian Energy Sector needs to encourage the creation of independent entities owning, operating and maintaining the T&D system. Future versions of the model will need to incorporate the anticipated results of the transmission infrastructure projects to improve validity. Stakeholders whose interests are most at risk like smallholder farmers, indigenous communities and informal charcoal producers must be empowered with equitable participation in decision-making processes. With collaboration and careful regulation, the suppressed electricity demand of Liberians can be met in a cost-effective way with reduced dependency on imports, while bolstering the local economy and preserving its forests.

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