Exploring the Emergence of Renewable Energy Grids in Developing Countries with Agent Based Models

by

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Dedication

To all the L's in my life and my one S, Lindy, Leidy, Luis B., Luis A. and Sidney, and to God who's strength never left me even when I left him.

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We may be fooled to think that getting a Ph.D. is an individual accomplishment, but its not. Many people are involved in pushing the student towards the achievement. While at some points the work is incredibly lonely and in the end the student is responsible, no one would be able to make it without help and direction from a wonderful group of people.

I was incredibly blessed with the committee that guided my work. My advisor, Shelie Miller, was patient, kind, and incredibly insightful. From the moment we met at a meeting not even planned, to the very end, she saw things in me that I could not. Her insistence that I could come up with a unique research theme separate from her work scared me to pieces, but in the end was one of the best things she did for me. Shelie provided an incredible wealth of knowledge, encouragement, and even tough love when it was necessary. She provided me with freedom to pursue academic endeavors and wise guidance to turn them into useful contributions my field. Not to mention she was even crazy enough to join us on a trip to Liberia and go fishing with her bare hands in the muck!

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to give her or when I was gone for months at a time traveling through Africa. Instead of wanting me to stay home she took what little vacation time she had and spent it with me volunteering in programs I was involved with. She has served as a counselor for SWB, a teacher for EHELD, a career advisor for students, and continuous to give her time and energy freely to make those programs succeed.

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Overview

The following work creates Agent Based Models (ABM) and tools for policy planning and appropriate deployment of renewable energy for electricity generation in developing countries. At the surface, deployment of renewable energy technologies can be considered as an exercise in least cost analysis of the different resources available in the region. However, the problem is of a more complex nature. Renewable energy is geographically constrained, as are the demand points that require the electricity generated. A least cost delivery system is needed to appropriately deploy renewable energy resources and transmit electricity.

Further, the choice of different resources to be deployed and the priorities for supply given to the demand centers is influenced by the preferences of stakeholders, including policy planners, investors, local governments, and key decision makers. For example, it is common for urban demand centers to receive priority in the provision of services and infrastructure, including electrification (World Energy Council 1999).

Each step in the development of a new electricity grid or electrification process affects the possible next steps and the final outcomes that are attainable by the system, a concept known as path-dependence. This means that "history matters" (Arthur 1994) and upon the completion of each step new possible optimums for the remaining areas awaiting development must be calculated.

The objective of this work is to create policy-planning tools that can be utilized by different stakeholders for the deployment of renewable electricity in least developed countries. This is an important objective that addresses gaps that have been identified by both Industrial

Ecology and Energy Modeling literature. Industrial Ecology presents a call for more descriptive models and away from prescriptive models (Dijkema and Basson 2009). It also calls for the consideration of social contexts in which systems develop and tools that can capture dynamic emergence instead of static snapshots (Ehrenfeld 2009, 2007).

Tools for energy planning based on different modeling techniques are available throughout the literature. However, these tools have not provided adequate support for less industrialized countries (LIC), their complexities, and policy considerations (Bhattacharyya and Timilsina 2010; Urban and colleagues 2007). Urban and colleagues point in particular to the lack of focus on off-grid renewable energies, poverty, and rural energy programs. (2007). Bhattacharyya and Timilsina point to models that can capture developing countries' particular contexts as a key input for future policy formulation (2010).

Literature also points to the use of simulations, bottom-up hybrid models, and disaggregated approaches as the most promising solutions for future models in developing countries (Bhattacharyya and Timilsina 2010; Urban and colleagues 2007). These authors warn that the tradeoff of such models is increased complexity, high data requirements, and high skills needed for use.

Clean energy solutions, including electricity and clean cooking facilities, are key to the accomplishment of the millennium development goals (MDG) issued by the United Nations to eliminate poverty (International Energy Agency 2010). While all MDGs are tied to clean energy, there is not a particular MDG devoted to clean energy and focused policy efforts will be necessary to achieve the desired increases in this sector (International Energy Agency 2010).

Energy is directly tied to gross domestic product (GDP) but the benefits that can be achieved through electrification go well beyond the economic. Deichmann and colleagues suggest that the correlation between energy and human development index (HDI) is even stronger than that with GDP (2011). Literature also points to increases in business activity, better education, reduction of gender bias, better health, and cleaner indoor air, as some of the additional benefits that can be achieved through the provision of electricity and clean energy (Komatsu and colleagues 2011a; Daka and Ballet 2011; Abanda 2012; Maiga and colleagues 2008; Kooijman-van Dijk and Clancy 2010; Kooijman-van Dijk 2012a).

It is then no surprise that significant activity in electrification research for LICs and in particular rural areas abounds. However, these analyses have consistently viewed the issue as a question of expanding grid coverage in a region through the extensions of a central generating structure versus the deployment of small house or community level renewable energy electricity technologies (Parshall and colleagues 2009; Sanoh and colleagues 2012; Levin and Thomas 2012). Most of the grids considered are fossil based and in many cases already taxed and inefficient. Countries in Sub-Saharan Africa for example have electricity grids that face frequent black outs, poor maintenance, and low quality of service (Foster & Steinbuks, 2009). Expanding a struggling infrastructure may result in reduction of energy services for people who already received them.

Economic parameters are widely used as decision basis. This ignores the ways in which humans are involved in the planning process. Not all decisions are based on economics and imperfect incentives exist when dealing with coupled needs of LICs. Preferences of stakeholders play a big role in the way a system evolves. For example, stakeholders may have a source of funding that explicitly encourages solar photovoltaic (PV) technologies. Even though this is one the most expensive technologies and its applications are limited, the stakeholders may put emphasis on them at the cost of other opportunities with better economic performance.

The work presented here seeks to create models that are user friendly for stakeholder engagement, applicable for *in-silico* experiments of policy development, and inclusive of the complexities of renewable energy, human actors, environmental considerations, and the interaction between the three spheres. The models attempt to provide descriptive scenarios that include non-economic metrics for the support of policy, trade-off analysis, and planning exercises.

This work expands the literature through four main considerations:

1) Analyzing the "clean slate" case where no existing infrastructure is present and therefore can't provide ancillary services for development of renewables. This is practical for areas of LIC with little or no infrastructure.

2) Considering the deployment of renewables as the only option eliminating the use of fossil fuels and nuclear energy.

3) Including parameters beyond the economic that affect the way the delivery infrastructure would emerge and evolve, such as job generation, fuel portfolios, equality, and development. These parameters capture the preferences that stakeholders may present when developing policy or electrification plans and the path dependence that is inherent in the development process.

4) Providing a novel tool for trade-off analysis that fills the literature gaps identified above.

1.2 Research Questions

These contributions come from three main research questions:

1) How will renewable electricity networks develop without the presence of existing infrastructure or fossil fuels and nuclear energy?
2) How will stakeholder decisions and the interactions with technical and environmental spheres affect the resulting networks?
3) Can policy-planning models capture these interactions and provide useful tradeoff analysis?

Providing an answer to Question 1 allows this work to inform the case of many LIC where little infrastructure is present or, if present, can't be relied upon to increase electrification. It also includes the geographical limitations of renewable energy potential and the demand points that need to be serviced.

Question 2 allows the consideration of the interaction of between social, environmental, and technical spheres called for in Industrial Ecology literature. These interactions categorize the electrification process as a Socio-Technical system in which social decisions and interactions clearly affect the technical and environmental facets of the system's operation. Because of the environmental nature of renewable energy, the environmental considerations are particularly strong in the renewable electricity deployment process.

With so many different parameters and considerations present in the deployment of this system tradeoffs between different goals are bound to appear. Question 3 is focused towards discovering modeling approaches that can be used for tradeoff analysis and not as a prescriptive tool. This would create interesting avenues for interactions between industrial ecologists, modelers, policy planners, decision makers, stakeholders, and investors. It would also provide scientifically based information for the decision process.

1.3 Method Overview

To address Research Questions 1 and 2, Complex Systems Science (CS) or Complexity Theory is used. CS moves away from reductionism and seeks to capture the emergence of unexpected macro-system behavior that results from apparently simple interactions between system components (Mitchell). What constitutes complexity is hard to define, even by the experts in the field. Perhaps because the science of complexity is trying to deal with diverse and dynamic issues from a plethora of disciplines (Waldrop 1992). Some examples of these systems are the collapse of the Soviet Union, the crash in the stock market on a single Monday in 1987, sudden extinctions, the process in which the brain creates feelings, and life itself (Waldrop 1992).

One of the modeling tools that has gained popularity in CS is Agent-Based Modeling (ABM). ABM seeks to capture macro-level behavior by modeling individual entities that make up systems and the rules that govern their interactions within the system. These software entities are then allowed to interact in a virtual world. The result the modeler is seeking is the *emergence* of the macro-scale state and behaviors of the system. For example, a modeler may create thousands of virtual sardines and provide them with simple rules for navigation such as the maximum and minimum space they should leave between themselves and another sardine and their preferred direction for swimming. A model containing thousands of these sardines may allow the modeler to observe the flocking behavior of the sardines into a bait ball and how changing the rules of interaction may dissipate or create the ball.

The emergence of renewable electricity grids and the way that social interactions affect that emergence is explored in Chapter 2 of this dissertation. Chapter 2 develops an ABM with practical interphases for ease of stakeholder participation. It attempts to capture the complexities of renewable energy deployment, geographical considerations, unique situations in developing countries, path-dependence, value judgments, and social and environmental contexts in which new systems develop, while providing a solution for the planning of fully renewable based electricity systems.

Through this model the research goes beyond simple analysis of technical and economic feasibility to the consideration of best practices for the development of infrastructure for electricity delivery with considerations of stakeholder preferences for renewable energy sites and balances between centralized and decentralized decision making. This initial ABM studies the delivery system as a key factor for minimizing total cost.

The model captures the emergence of renewable electricity delivery grids by creating representations of the environment and the renewable potential in it, the populations and demand centers that require electricity, the production units that would use the resources in the environment to provide electricity, the transmission lines that would be needed to carry the electricity, and a central planner or stakeholder that determines the strategies and preferences for different deployment. Through these agents and the rules created for their interaction the model becomes a test bed for the way that stakeholder interactions and preferences affect the costs and decentralized mix of generation units in a stylized world with no infrastructure or fossil fuels.

To apply the discoveries form Chapter 2 to a more specific context and to answer Research Question 3 the case study of Liberia, West Africa is introduced. Liberia is the least electrified country in the world (Africa Energy Unit 2011) and a typical example of LICs, which pose the largest challenge for electrification increases (International Energy Agency 2010). Before applying the ABM created in Chapter 2 to the case study, an individual analysis of Liberia's renewable energy potential, its suppressed rural residential demand, and opportunities to fulfill demand through fully decentralized renewable energy projects is created in Chapter 3. This serves as initial evidence of how renewable energy can fulfill large electricity demands in certain regions. It also sets up the dissertation for deeper considerations of the Liberian case through the use of the ABM for policy-planning and expanded considerations of stakeholders' roles in shaping the economic and technical performance of an electricity system.

Chapter 3 presents a Monte Carlo analysis of the suppressed demand in Liberia's rural areas. The urban populations are ignored due to the established plans for electrification of those areas (Africa Energy Unit 2011). The obtained suppressed demand is compared to a the Liberian renewable energy potential gathered through literature review of the subject. The Chapter then provides the cost of deploying only one renewable technology in Liberia at a time and includes the provision of decentralized diesel generation as a comparison to the costs of fossil fuels technologies.

The Chapter stands on its own as an analysis of the Liberian situation and has been published in the *Renewable and Sustainable Energy Reviews* (Alfaro and Miller 2014). However, it also provides the data and background necessary for Chapter 4 and the expansion of the ABM in Chapter 2 to more explicit cases.

The expansion of the initial ABM pushes on Industrial Ecology (IE) boundaries. The work serves as an attempt at bridging the gap between analyzing systems and helping shape them with responsible actions, a call present in the IE literature (Dijkema and Basson 2009). The original model is expanded with a geographical information systems (GIS) solution to including country specific data and a new level of stakeholder strategies, which reflect value judgments for complementary objectives of rural electrification. The expanded ABM is illustrated through its application to the Liberian rural case as a tool for multi-objective policy planning and tradeoff analysis.

The inclusion of specific data consists in the incorporation of GIS layers for the creation of realistic environments and heterogeneous agents in the model. GIS data on population, political boundaries, and renewable energy potential are among those considered. Data is also included on the specific technical performance and economics of three renewable energy technologies, small biomass direct combustion or gasification, small hydro, and solar photovoltaics (PV).

Expanded value judgments and human context are included through four strategies sometimes used when planning renewable energy projects:

1) Using renewable energy projects to create new jobs (Wei and colleagues 2010; IRENA 2011)

2) Considering economic stimuli created within a community when renewable energy projects are established (Buchholz and Da Silva 2010; Dinkelman 2011)

3) Using investments in renewable energy to increase equality and social justice. This is particularly important in Liberia where recent policies call for wider inclusion of rural areas and less developed regions (Africa Energy Unit 2011; Ministry of Lands Mines and Energy 2009; Republic of Liberia 2008).

4) Prioritizing deployment for larger pockets of population.

The result is a robust tool that can be used for scenario development, policy planning, stakeholder engagement, and new electrification efforts. This expanded model acts as an *in-silico* laboratory for experiments that can't be conducted on the real system. It allows stakeholders and IE practitioners to explore the dynamic emergence of the system under the influence of the social, and environmental context. Such a tool is an expansion of IE tools that have been criticized for ignoring the context in which systems develop and for being static in nature (Ehrenfeld 2009).

Chapter 4 is used to answer Research Question 3. It shows that policy planning instruments can be provided that capture the different complexities in LIC, the interaction between social, technical, and environmental spheres, and the emergence of dynamic systems under the tradeoffs created by value judgments of decisions taking place. However, the Chapter warns that these tools are not a substitute for stakeholders or decision makers. Decisions, tough ones, must be made under sounds and responsible information. The tools provided in the chapter are an example of how industrial ecology practitioners can provide these interventions and facilitate interactions with stakeholders in a scientific and responsible manner.

Figure 1-1 below shows a schematic of the research methodology used in this dissertation.

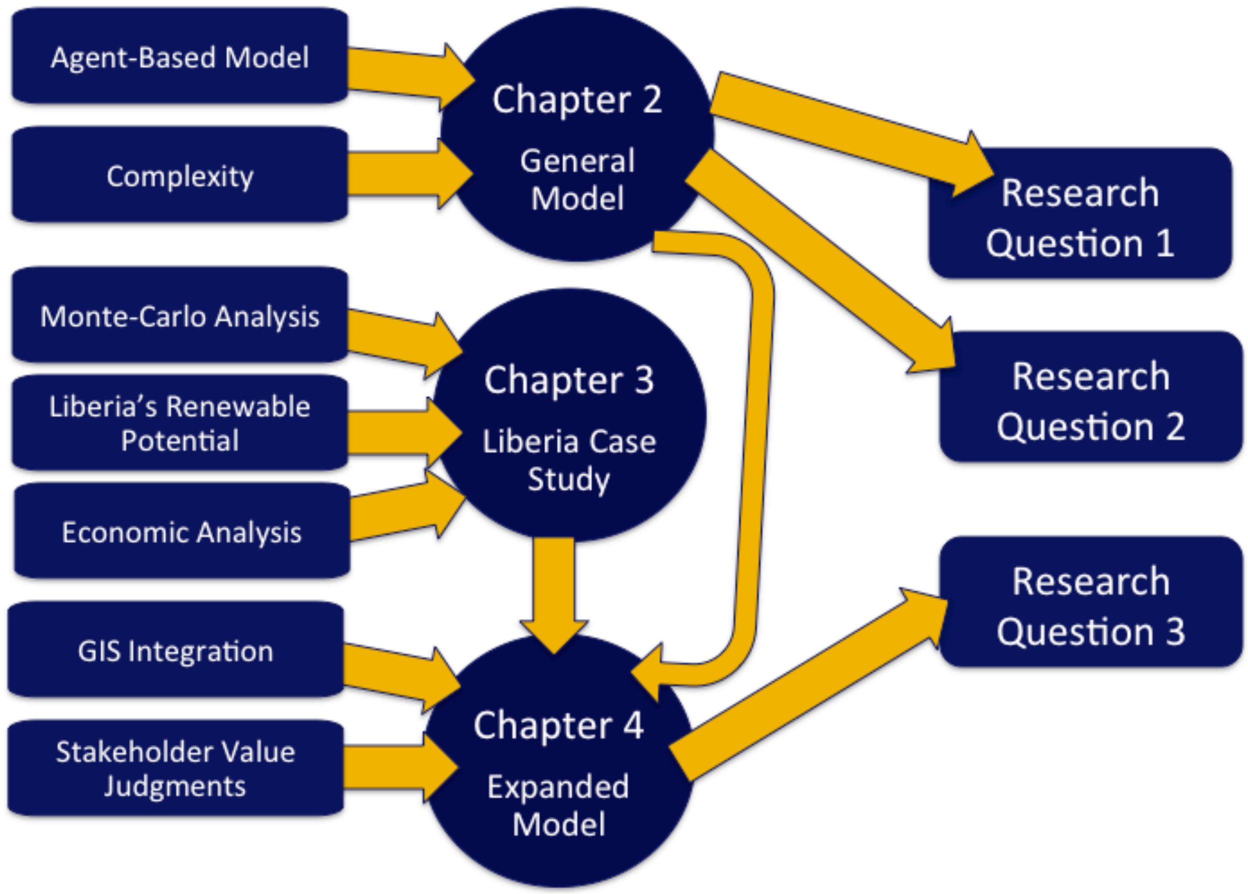


Figure 1-1: Schematic of research methodology applied to renewable electricity emergence in LIC

1.4 Renewable Energy Deployment

In LICs, efforts to incorporate renewable electricity have been fueled by two main objectives, increases in electrification and reduction of greenhouse gas (GHG) emissions (Abanda 2012). While reducing GHG emissions is an important aspect, this work focuses on the provision of electricity through renewable energy as a key to well-being and development in LIC (Kooijman-van Dijk 2012b; Komatsu and colleagues 2011b; International Energy Agency 2010). By analyzing the opportunities for renewable energy development without fossil based backups both goals are addressed.

Eliminating fossil fuel back-up options brings to the forefront concerns of renewable energy intermittency of service. These concerns can be reduced in LIC. Demand in LIC is orders of magnitude smaller than demand in industrialized countries (International Energy Agency 2010) allowing for storage solutions to be economic and creating novel load management opportunities. The focus of this work is on areas where intermittent service represents an improvement over the status quo. Literature suggests intermittency of service decreases the uptake of electricity and electrical appliances in businesses and entrepreneurial operations but appropriate communication about expected hours of service or expected blackouts allows users to adapt (Kooijman-van Dijk 2012b; Ibrahim and colleagues 2002).

Three main technologies are used in the models, solar PV, small hydro, and direct combustion or gasification of biomass. In the case of solar PV the cost of batteries is included in calculations to maintain stable service. For small hydro the models do not consider the maximum capacity of the resources but a limited value. This allows an increase in the probability that the base demand will be serviced. The assumption is also made that connections to these projects will be based on a power basis and not units of electricity. Examples of this type of load management are available in the literature such as the Mein River pilot project in Liberia (Winrock International 2011a, 2011b). Connections are provided with a maximum wattage and a breaker that disconnects the load if the user exceeds the power allowance. The result is a forced capping of the peak demand for easier load management. Finally, biomass technologies presented here are considered dispatchable. The stable performance of the technology even under different feedstocks allows for storage of fuels and load management.

1.5 Complex and Socio-Technical Systems

As mentioned earlier the deployment of renewable electricity without the support of existing infrastructure and fossil fuels represents the emergence of a complex system. It has already been stated that experts in the field are still defining complexity. By extension the same is true for complex systems. However a good starting point is the definition by Mitchell (2009):

> “*a system in which large networks of components with no central control and simple rules of operation five rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution.”*

Some divide complex systems in complex adaptive systems (CAS) and non-adaptive systems. CAS show different ways in which the subsystem parts react, learn and evolve in response to each other. Non-adaptive complex systems lack this distinction, for example a hurricane already in motion (Mitchell 2009).

In our example the stakeholders make decisions on the creation of production units, production units use resources in the environment, the environment changes the resources available according to the production units being created, populations change their costs of electrification according to new production units being created and other populations being electrified, and all this information is relayed back to stakeholders who are now facing a new state of the original problem. This work also considers situations in which both centralized and decentralized decisions are made. However, even when central decisions are taking place, the changes in the environment and resulting changes in other parameters are not controlled by a centralized organization making the system a CAS.

Because electrification is largely dependent on the social interactions, decisions, and desires present, it can be classified as a particular type of CAS, a socio-technical system (STS) (Nikolic and Kasmire 2013a). Researchers first tried to model societies with ABM in 1990 (van Dam and colleagues 2013). The applications of this method have had explosive growth.

In particular STS has found traction in the IE field. Core to STS studies is taking in consideration the connections between the social, natural, and technical fields (Dijkema and Basson 2009). Using and recognizing these interactions provides opportunities for IE to guide systems into a promising future (Ehrenfeld 2007).

STS modelers place emphasis on providing description and possibility and not predictions (van Dam and colleagues). This is an important part of the work presented here. Because modelers' and stakeholders' objectives are often not aligned (van Dam and colleagues), it is also important that the modeling be guided with stakeholder input and that stakeholders are provided with opportunities to verify the model and modify it if necessary. This would allow industrial ecology practitioners and decision makers to engage in an interactive and iterative planning process with accountability and a responsible and sound framework. While the work presented here aims to accomplish this, only one iteration of the modeling process has been finished.

1.6 Liberia

Liberia, West Africa, has 3.7 million people and an area of just over 111,000 km^2 (Hamdan 2010; Republic of Liberia 2009). It is a country rich in natural resources with iron ore and diamond deposits, tropical climate, large forestry potential, and more than 40% of the remaining Upper Guinean Rain Forest (Republic of Liberia 2008; Milbrandt 2009; Conservation International 2007). Its renewable energy potential is also significant. Small hydro, solar, and biomass lead the way in possibilities (Africa Energy Unit 2011; Milbrandt 2009). Coastal and off-shore wind are also of great potential (National Renewable Energy Lab). While recent discoveries of fossil fuels have been made, most of Liberia's fossil supply comes from abroad creating fuel insecurities. Recently the country had more than one week of fuel shortages where diesel prices increased to $10 per gallon and public transportation, on which most Liberians depend, increased in cost by 100% (Browne, 2014, and personal communications).

Freed slaves from the United States of America sponsored by colonization societies arrived in Liberia beginning in 1820 and founded the country in 1847 (Wikipedia.org). These pilgrims became the ruling elite in Liberia institutionalizing a class divide that lasted over 130 years. A military coup in 1980 was followed by upheaval and a second coup in 1989 that ushered a brutal civil war. The war lasted for 14 years with short periods of stability. The Accra agreement of 2003 brought peace and in 2005 the first democratically elected woman in Africa, Ellen Johnson Sirleaf, took office as president of Liberia (Johnson-Sirleaf 2009; Wikipedia.org).

The remnants of Liberia after the war were a far cry from its period as a jewel of Western Africa in the early 80's. Almost all infrastructure was destroyed and looted (Republic of Liberia 2008). Some 250,000 to 520,000 Liberians were dead and millions were displaced (Wikipedia.org). The country had to be restarted from scratch.

While this is a tragic turn of events, it offers Liberians and their leaders an opportunity to take significantly different roads towards development than those used in the past. The energy sector is one of the key areas for the redevelopment and a prime opportunity for deploying new solutions.

Appropriate tools for policy planning and stakeholder involvement can go a long way in helping evaluate the opportunities and priorities for Liberia and its future electricity development. A strong plan is already in place to electrify the capital city of Monrovia and other important demand points (Africa Energy Unit 2011). However, more than 50% of the population in rural areas will remain unelectrified. Further, the main supply for the planned grid will be fossil based.

This dissertation provides tools that could be used in the planning and development of renewable electrification for the remaining population of Liberia. Such tools may help the country leap-frog over traditional paths and arrive at a universal electrification system with lower GHG and improved environmental performance compared to others in the region.

1.7 Publication of Chapters

Chapters 2-4 were developed as manuscripts for publication. Chapter 2 has been submitted to the journal *Renewable and Sustainable Energy Reviews*. Chapter 3 has been published in the same journal (Alfaro and Miller 2014). Chapter 4 was prepared as a contribution for the special issue on Complexity of the *Journal of Industrial Ecology*.

Although the manuscripts were submitted as separate pieces they are interdependent. Chapter 2 creates an ABM foundation for the work carried out in Liberia in Chapter 4. It also presents the initial proof of concept for the use of ABM in cost minimization, policy planning, stakeholder preferences, and the case of a clean slate region with no existing grid. Chapter 3 provides a necessary investigation of Liberia's suppressed demand in rural areas and the feasibility to supply it through renewable energy. This is critical for the application of the ABM model created in Chapter 2 and its expansion. Finally Chapter 4 integrates the models and analyses of Chapters 2 and 3, and expands the tools towards a robust, user friendly, policy-planning tool that incorporates value judgments, multiple objectives in electrification, and tradeoff analysis.

Chapter 2

Using Agent Based Modeling for Infrastructure Planning in the Deployment of Renewable Energy in Developing Countries

2.1 Abstract

Many seek to mitigate greenhouse gas emissions when planning electrification projects in developing countries. Research to date often compares the expansion of centralized, generally fossil-based, electricity delivery systems with decentralized renewable electricity generation at the demand point. However, existing grids in developing countries may not be suitable for expansion and distribution of renewable based electricity generated away from demand points is ignored. Tools available do not analyze different decision strategies used by stakeholders to plan a distribution system. Given the longevity of infrastructure projects, development decisions today can constrain future choices due to path dependence and can highly influence the total cost of the delivery network.

This study presents a novel application of agent-based modeling to identify decision strategies that result in least cost electricity delivery infrastructure systems using a mix of centralized and decentralized generation powered by renewable sources. It contributes to the existing literature by considering the case of a clean slate where no initial system is present, developing a delivery grid based completely on renewables, illustrating the decision schemes of stakeholders, and including path dependence and non-economic preferences.

Results show that when available resource potential is high compared to maximum demand, the lowest cost strategies have a large decentralized mix and are achieved through a bottom-up scheme focused on location near demand points. When demand is high relative to available resources, the least cost strategy is to emphasize a top-down decision scheme focused on expansion of clusters created around central resources.

2.2 Introduction

Over 1.4 billion people have little or no access to electricity (International Energy Agency 2010). Most of these people live in developing countries, rural and secluded areas, with low population density and electricity demand. However, these populations are endowed with abundant renewable resources for electricity generation. For example, Deichman et al. asserts that in Sub-Saharan Africa, the least electrified region in the world, countries have 10 to 12 times the renewable energy potential needed to satisfy their consumption (Deichmann and colleagues 2011).

Grid extension (GE) and decentralized generation (DG) are often considered the two main pathways for electrification of these areas, and their relative merits are debated, The definitions of what constitute each pathway vary (see for example (Ackermann and colleagues 2001)). In this paper, GE is considered as the expansion of existing electricity generation capacity and/or delivery networks to reach new demand centers and increase electrification rate. The expansion of the delivery network may include installation of new transmission lines, transformers, and substations. DG is contrasted to GE because it involves creation of new electricity generation and delivery systems close to the demand center that is to be serviced. Existing infrastructure is not used for this purpose and the transmission lines to be created are generally smaller in span, voltage grade, and cost.

Much work has been done contrasting relative merits of GE and DG (among others (El-Khattam and Salama 2004; Kaundinya and colleagues 2009; Hiremath and colleagues 2007; Hemmati and colleagues 2013; Levin and Thomas 2012). Most literature available uses case studies of different countries to draw conclusions about the best pathway for increasing electrification in that context.

Levin and Thomas analyze the choice between GE and DG in 150 countries correlating it to population, demand, cost of transmission, and cost of generation. They arrive at a parameter y* that determines the demand at which a population is more economically served by GE. They also utilize a network algorithm to determine the shortest span of GE that serves the majority of the country. The result is that each country presents one major grid with several DG sites (Levin and Thomas 2012).

Deichman et al. also use network algorithms to determine the expansion of a grid to economically feasible areas (Deichmann and colleagues 2011). In contrast with Levin and

Thomas, Deichman and colleagues allow several centralized grids or medium voltage clusters to expand. They use three countries as cases studies, Ethiopia, Ghana, and Kenya. Both the Levin and Deichman studies use a greedy-algorithm, which adds largest populations to GE first.

Parshall et al. present the case study of Kenya (Parshall and colleagues 2009). They developed a geographically based model to determine the areas of least cost expansion of the grid. They compare GE to DG using diesel and PV technologies only. They also include penetration rate, the number of households connected at each node, as a consideration in their model.

Sanoh et al. build on Parshall's work and create a case study for Senegal (Sanoh and colleagues 2012). They compare the maximum distance of medium voltage lines that can be built before exceeding the cost of DG through diesel or PV technologies. A minimum spanning tree algorithm is used to correlate the results to actual GIS populations in the area of Leona.

These studies suggest that areas suitable for DG have low electricity demand, large distance to the existing grid, and low population size or density. They recognize them as typical rural isolated areas. Deichmann et al. conclude that only rural areas can be economically served through DG (Deichmann and colleagues 2011).

This paper contributes to the existing literature through the creation of an agent-based model (ABM) that investigates different decision strategies for designing distribution systems for renewable electricity. The model focuses on the capital investments needed to create the renewable energy delivery infrastructure. It provides four main contributions to the literature. First, it studies a "clean-slate" hypothetical world with no existing grids, akin to many remote, unelectrified areas. This allows for scenario analysis that is freed of the locked-in infrastructure investments of past which typically support fossil fuel consumption, an assumption that is particularly appropriate for unelectrified regions. Second, it analyzes the emergence of infrastructure with a suitable mix of GE and DG based solely on renewable energy, rather than comparing decentralized renewables to centralized fossil-based infrastructure. This means that both the opportunities for renewables to be used at a load center and for renewables to serve as centers for distribution grids are analyzed. Third, the work uses the magnitude of renewable energy potential as an added parameter to consider for characterizing opportunities for DG. Finally, the work models the evolution of the network under decision strategies of stakeholders that include preferences for resource deployment beyond purely econometric concerns and the path dependence inherit to development based on those preferences.

The paper draws conclusions from this stylized general situation that can serve as heuristics for future renewable energy infrastructure development. Because the ABM is created in an easy to use and graphically interactive freeware, it can serve policy and educational planning sessions.

2.2.1 Grid Extension and Decentralized Generation

GE requires expansion of existing infrastructure to transmit electricity to new demand centers. This paper uses the concept from network science of weakly connected components or clusters to refer to the existing infrastructure that can be extended. Weakly connected clusters are a collection of nodes that can be reached from any other node in the cluster through at least one path (Newman 2010). For our purposes nodes are production units (existing or planned generators) and demand centers (populations). The paths that connect those nodes are transmission and distribution lines. In other words, a weakly connected cluster is a group of demand centers and generation facilities connected through a web of electricity supply lines. An example of this can be seen in Figure 2-1, which shows three different weakly connected clusters. For simplicity the paper will refer to them as "clusters".

GE results in a higher degree of centralized generation meaning that most nodes in the electricity distribution system are part of the same cluster. Developed countries followed GE as the preferred pathway to electrification.

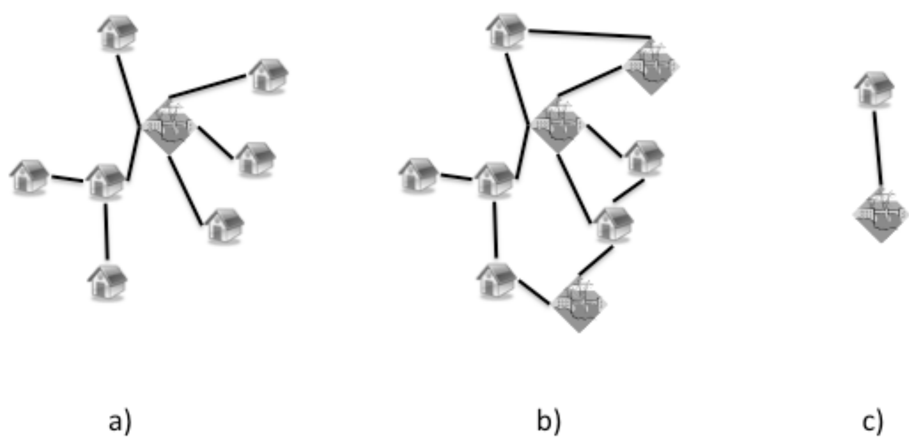


Figure 2-1: Example of 3 different clusters

Notice the number of nodes or arrangement of the links and nodes do not determine a cluster, only the fact that all nodes are connected to each other by at least one path or web of connections. All nodes with any connections are part of a cluster.

GE and the interconnection of several generation units provides the advantages of rotating generators and reserves for system reliability, reducing the total number of generators running with no load, and providing flexibility for power transfers (Glover and colleagues 2012a). Redundancy is avoided in GE and point source emissions are moved away from main populations. Thanks to larger connected demand, economies of scale in generation and transmission can be obtained.

However, GE can present environmental, economic, and stability concerns. GE, and its associated centralized planning, has been criticized as leaving large gaps in electrification, creating class divides and national debt, and causing environmental degradation by relying on fossil fuels and causing deforestation (Hiremath and colleagues 2007, 2009; Deichmann and colleagues 2011).

This study defines DG as the production of electricity separate from existing clusters, which does not involve extension of existing infrastructure. In this way, low voltage wires in the range of 11 to 33 kilovolts (kV) and transformers are sufficient for electricity to reach the end users. The new generation and electrified population become a cluster that is available for expansion later if necessary.

This method usually requires the investment in a larger number of smaller generation facilities (from a few kW to 50 MW). Due to their size they tend to have higher costs per kW of installed capacity (Abou El-Ela and colleagues 2010). Decentralized system result in a larger number of production units or generators and larger management complications may be experienced. The number of production units means that human capacity must be available at several locations in order to maintain, fix, and run the entire delivery system.

In exchange, due to DG lower grade cables and shorter distances between generation facilities and populations serviced, electricity can be provided in remote areas, avoiding major capital investments in transmission infrastructure, habitat fragmentation, and with reduced line losses. Structural stability of a network may increase by adding DG. In India for example, long connection lines are being replaced by shorter segments to make way for a more structurally sound system as electrification progresses and new villages are added to the grid (Mukhopadhyay 2007).

Although often discussed as distinctly separate entities, elements of both GE and DG can be included in an overall electrification strategy. Even when dealing with existing fossil-based electricity networks the two paths can be complementary to reduce the overall cost of a region's electric infrastructure while ensuring full access to electricity. Indeed, Bazilian et al. point out the need for the use of both large scale centralized projects and DG to achieve universal energy access (Bazilian and colleagues 2012). Some countries have found it economically necessary to include both approaches in their electrification efforts. Brazil, for example, embarked in a DG program in remote areas where GE was not economically feasible (Gómez and Silveira 2012).

A DG can eventually become part of a larger cluster further complicating the distinction between the two approaches. For example, a DG project may service a population that grows until an economically feasible connection to existing transmission infrastructure becomes apparent, prompting the original DG project to become part of the GE efforts. This system then becomes a hybrid, or what the World Bank calls "organic grids" (Africa Energy Unit 2011). Small generators can also be grown into a low voltage grid, or a micro-grid. In Portugal, it has been suggested that such DG can be connected to a grid and become an asset to the larger system by providing enhanced reliability through islanding, or the isolation of segments of the grid in case of black outs (Costa and Matos 2006).

Renewable energy resources are often geographically constrained in contrast to fossil fuels, which can be moved to desired locations when adequate infrastructure exists. Generation facilities utilizing renewable resources will have to be located near the source. A tradeoff develops between locating electricity generation near demand centers to avoid high transmission infrastructure costs and line losses against the need to locate generation facilities at the source of the renewable resource. When planning for the deployment of renewable energy resources, a balance between GE and DG will most likely be needed. The right balance between the two pathways allows minimizing the cost of the distribution network while utilizing the right resource locations and supplying universal electrification.

2.2.2 Top-down and Bottom-Up Decision Strategies

In addition to GE and DG pathways, this paper considers two frameworks for decision-making, top-down, and bottom-up. Top-down planning is defined here as electrification plans developed by a central entity or stakeholder. In this model it occurs through the selection of preferred renewable resources locations for deployment by a central agents valuations that then focuses on connecting load centers economically to those resources.

Central planners' preferences have a high weight in this strategy. For example, if a central planner is more inclined to utilize the largest resources available first, the transmission and generation infrastructure will tend to favor that goal. In the model this strategy will be analyzed through three different central stakeholder preferences, the largest resource available, the most economic resource for large populations (mimicking urban center preferences), and central resources.

A bottom-up approach, in contrast, depends on the participation of many stakeholders. In this model it is portrayed through agents individually determining the best options for their electrification and providing that information to the central planner who makes decisions based on that information. For example, a community with an economically feasible GE option may prove that a nearby micro-hydro project presents a cheaper infrastructure investment. The central planner using a bottom-up approach as defined in this paper would consider the demand point suggestion first instead expanding resources she has already deployed. The community would be allowed to integrate the micro-hydro project to the overall portfolio of electricity infrastructure.

With the bottom-up strategy local authorities and stakeholders are able to weigh-in on the planning of the electricity distribution in a participatory manner, even though a central decision may still be made. Bottom-up frameworks, as defined here reflect a wider preference range, a larger focus on demand site needs, and less focus on particular sites for deployment.

It is important to consider that top-down and bottom-up refer to strategies followed for decision making while GE and DG are pathways that result from that planning. Top-down and bottom-up strategies help determine the appropriate DG or GE mix.

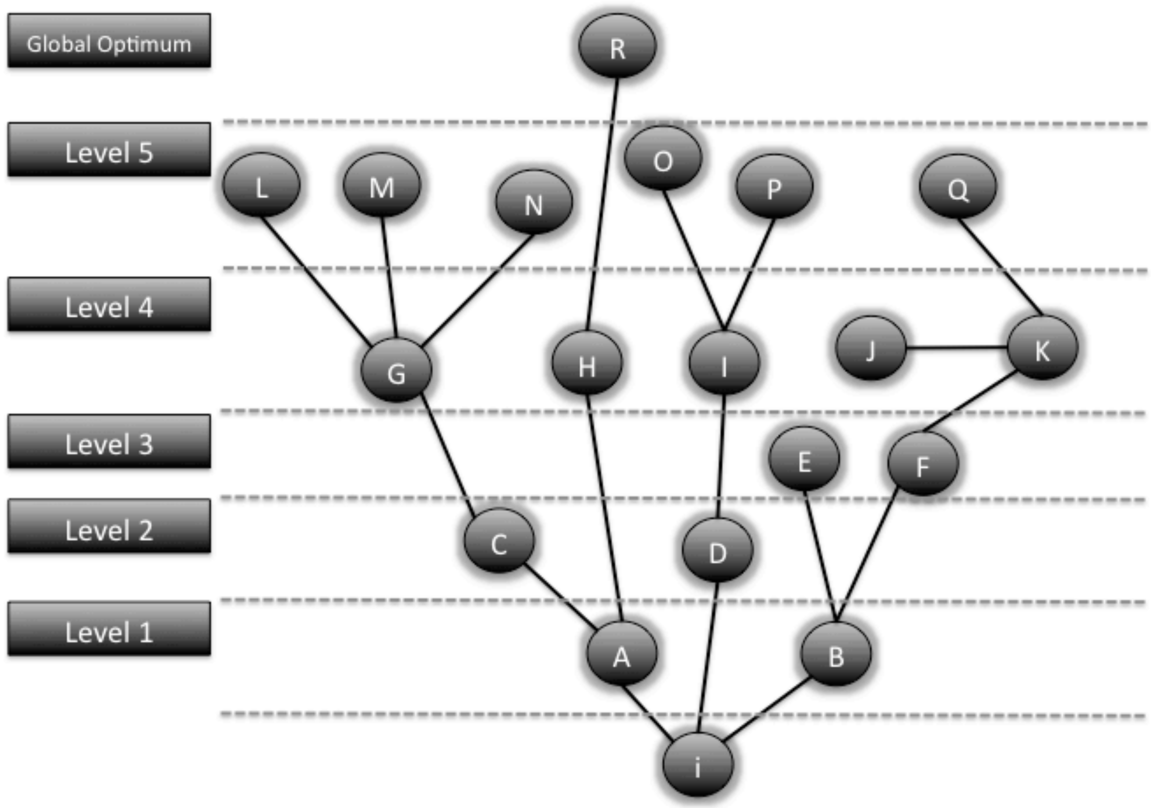


Figure 2-2: Illustration of Path-Dependence

Imagine each level in the figure is a higher level of development. A decision maker must make decisions following the lines. To get from i to the global optimum R, the decision maker must make decision A and then H. Making decision A and then C would mean R is lost as an option. Only G can be achieved after C. Further a decision maker who takes decision B losses the ability to reach L, M, N, O, P, and R.

In either situation the decision process is often path-dependent. Path-dependence can be defined as the concept that "history-matters" (Arthur 1994) to the future state of a system. Here, it is used in the sense that once a decision step is made, other opportunities previously available disappear and the new state of development changes the future steps that can be made and their relative new costs. In other words, the available opportunities change every time a step or development takes place. For an illustration see Figure 2-2. Path-dependence implies a need to examine what-if scenarios to ensure that the different strategies can be evaluated properly.

2.2.3 Agent Based Modeling

ABM is a framework that focuses on the micro-components of a system, their individual behavior, and their rules for interaction with each other and their environment. For a more extensive discussion of ABM one can look to (Nikolic and Kasmire 2013b). ABM has been used extensively in the modeling of networks. ABM often hopes to capture "emergence" or the display of system macro-behaviors that were not expected from the individual micro-components.

Many modeling techniques are used in the electricity and energy fields. However, their use and applicability in the clean slate scenario or the developing countries case presented here is limited. Urban and colleagues find 40 different models applied to developing countries, although only 12 are widely used (Urban and colleagues 2007). They find that the most useful models are those where imperfect market behavior and rationality are explored through simulations. They recommend that future models should be built for simulation processes and from the aggregation of smaller parts of the system. Bhattacharayya and Timilsina present similar conclusions and pose that none of the existing models adequately capture the complexities in developing countries (Bhattacharyya and Timilsina 2010).

This paper uses ABM because it provides flexibility and ease for including many aspects desirable in improving models for energy planning in developing countries. ABM follows a disaggregated model building approach and can include non-rational behavior or imperfect market choices, such as a stakeholder making decisions based on the largest resource available without economic basis. ABMs can include intuitive graphic user interphases that make them easy to use for stakeholders with little or no computer coding experience.

Other modeling techniques such as dynamic linear programing allow building simulations from an aggregate of smaller subsystems. These techniques rely on *memorizing* solutions for overlapping subsystems and seek to find the global optimum. ABM moves away from this practice and recalculates all options after each step allowing it to capture the path dependence of the evolving system. A global optimum is not guaranteed as the model is creating simulations of what can happen if the imperfect rules imposed on the system are followed. In other words, ABM creates descriptive simulations of the system and not prescriptive optimums.

ABM compiles these benefits in a simple graphic user interphase appropriate for stakeholders to use. A model that stakeholders can interact with and easily understand increases their involvement and buy-in positioning this paper as a possible policy planning tool as well as a proponent of generalizations for planning considerations. Through the ABM presented here stakeholders can create what-if scenarios and investigate their decision frameworks.

2.3 Methodology

This paper uses the ABM software Netlogo (Wilensky 1999). For clarity during the remainder of the paper, model components are capitalized to distinguish from their real world counterparts. The model quantifies the investment costs associated with the energy delivery system, comparing the impacts of different Decision Strategies, while limiting generation to only renewable energy options.

2.3.1 Model Assumptions

The model assumes that renewable energy potential throughout the World is dispatchable and of the same quality and kind such as biomass, or biogas. This allows the model to focus on the impact of the decision-making strategies and the cost and structure of the Delivery System. Similar assumptions have been used elsewhere by utilizing only one renewable resource to plan electricity supply. (Grossmann and colleagues 2012) used only solar PV to create a world system of electricity generation. The result is that costs of generation are the same regardless of the location of the production unit and allows the costs of the Distribution System to be considered in depth. The cost of electricity generation units is assumed from an average observation of renewable energy projects (EPA 2010; IRENA 2012a, 2012b, 2012c, 2012d). The cost of a 1 MW unit can be changed in the model by the user through the GUI but its change is not studied in this paper.

The population size, population's peak demand per capita, and the available electricity potential in the World are used as independent variables for investigation.

2.3.2 Model Components

The ABM contains five types of agents, namely Environment Agents, Population Agents, Production Unit Agents, Transmission Agents, and the Observer Agent.

The Environment Agents form the World in which the simulation is taking place. They contain information on geographic location and energy potential. Environment Agents form a squared World of 33 Agents per side and each Agent is 10 by 10 km. This translates to a World of 108,900 km^2. Environment Agents can be "inhabited" by other Agents who have access to the information within the Environment Agent. During the set-up of each model run, the available electricity potential in the World is distributed to each Environment Agent according to an exponential distribution. For each model set-up, many Environment Agents have relatively small to medium electricity potential and only a few Environment Agents have very large electricity potential. Observations in the real world agree with this type of distribution (for example see maps from the Iternational Renewable Energy Agency 2014).

Population Agents represent a load center with a certain number of people. The user provides the total inhabitants in the World and an annual electricity demand per person for the World. Overall populations of 0.25, 0.5, 1, 5, 10, and 50 million are evaluated in this study, with electricity demand per person of 100, 500, 1000, and 1500 kWh/year. These values provide a wide range of demand and population density for the model to analyze possible heuristics for future energy planning particularly in areas with little electrification. The population density range in the model is 2.3 to 460 pr/km^2. The average density in Africa, the region with the largest needs for electrification, is 36 pr/km^2 but countries like Mauritius and Rwanda are above the 400 pr/km^2 mark (United Nations 2013). Other countries like Niger have densities of 13 pr/km^2 and this paper makes the assumption that the densities in rural areas of some countries are significantly lower.

There are 50 Population Agents placed at random in the World. The population of each Agent is determined by an exponential probability distribution. As with electricity potential, this results in a realistic scenario with few Population Agents having very large populations and many Population Agents with small populations.

Production Unit Agents provide electricity and are created through the model run to satisfy the demand of the Population Agents. Production Units are created according to the decision schemes discussed below. They use the available electricity resource potential within their Environment and supply electricity to Populations via Transmission Agents.

Transmission Agents represent transmission lines and are created throughout the model run. They connect the Production Units with the Populations. Transmission Agents have different grades that depend on the distance spanned and the load carried. This model assumes five grades of transmission lines, which are deployed according to Table 2-1.

The Observer Agent plays a decision-making role predetermined by the user. The Observer manages the overall system and is considered a central planner that has access to all information in the model. The Observer executes one of the strategies outlined below.

Figure 2-3 shows a schematic of the agents in the model and their relationships.

2.3.3 Agent Interaction and Decisions Strategies

The five agents interact to create the delivery system following four decision strategies, Bottom-Up, Top-Down Largest Resource, Top-Down Largest Population, and Top-Down Central Resource, as seen in Figure 2-4. The strategies are based around the Observer preferences on the resources to be deployed and the manner to make expansion decisions. In the Bottom-Up strategy expansions are made with a participatory approach from all of the Populations, while the Top-Down strategies follow decisions for expansion as determined by the Observer only.

Table 2-1: Loadability* limits and costs of different line grades in the model

		Distance Limits					
Line Rating	Costs+ ($/km)	< 80 km	80-100 km	100-200 km	200-300 km	300-400 km	> 400 km
33 kV	23,000	0-14.5 MW	0	0	0	0	0
138 kV	90,000	14.5 – 156 MW	<143 MW	<117 MW	<91 MW	<68 MW	<57
230 kV	192,000	156 – 435 MW	143-399 MW	17-326 MW	91-254 MW	68- 188 MW	57-160 MW
345 kV	288,000	435–1275 MW	399-1169 MW	326 -956 MW	254-744 MW	188-552 MW	160 -468 MW
500 kV	417,400	>1275 MW	>11669 MW	>956 MW	>744 MW	>552 MW	>468 MW

*Loadability limits were determined adapting data in (Glover and colleagues 2012b)
+Cost data obtained from (Deichmann and colleagues 2011) for 33, 132, and 220 kV and extrapolated based on voltage for 345 and 500 kV. Deichmann and colleagues obtain their data from the Kenyan Ministry of Energy.

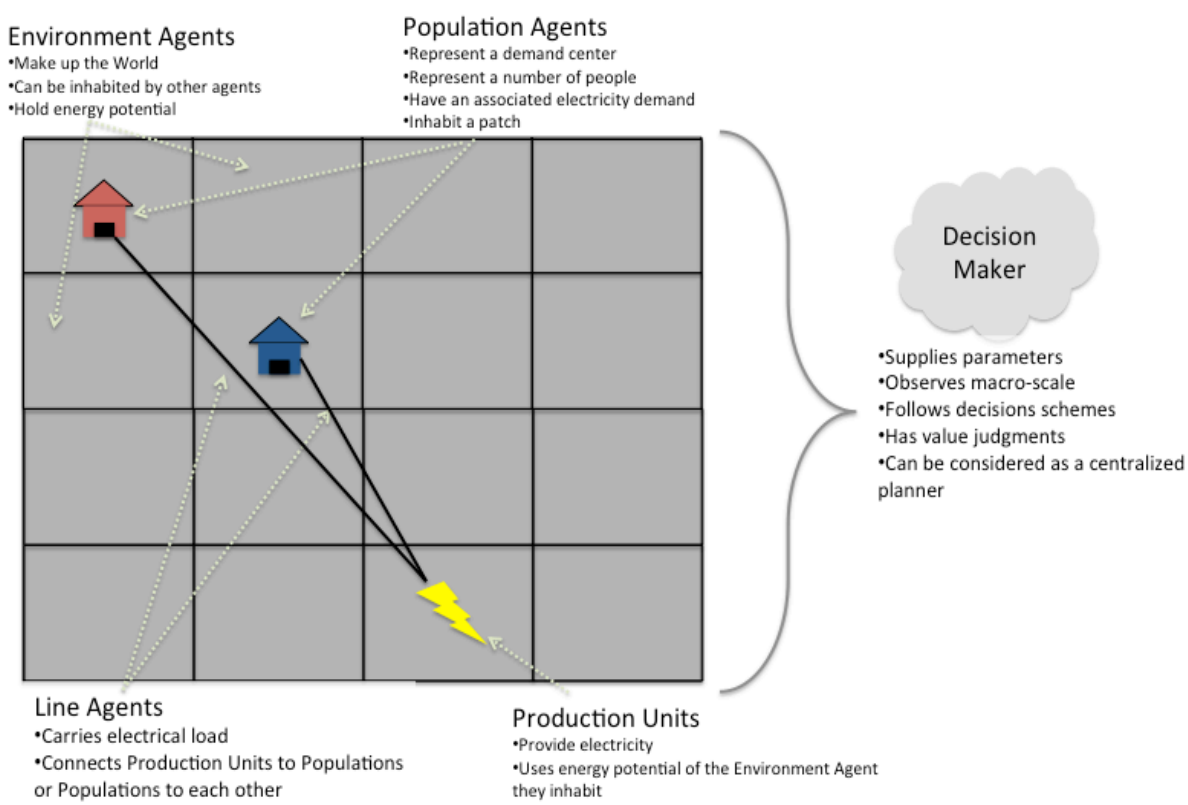


Figure 2-3: Schematic of agent types and their relationships

During model runs Populations can be Electrified (if all of their demand is met by a Production Unit), Incomplete (if connected to a Production Unit but not serviced in full), and Dark (if not connected to Production Units). In each strategy the Observer and the Populations calculate their costs of electrification. During each time step in the model all Incomplete and Dark Populations calculate their cost to connect to an existing cluster (C_{GE}), and their costs for decentralized generation (C_{DG}) normalized to the kWh. Complete equations for these calculations can be seen in the supporting information. Each Population Agent determines their cheapest alternative. The Observer has access to these same calculations.

To calculate the C_{GE} Populations find their closest connection socket to an existing grid. Sockets are Electrified Populations whose supplying Production Unit still has resources in its Environment that have not been used, or Production Units with available resources in their Environment.

When a Population connects to an existing grid there is a chance that the Cluster's Transmission will exceed their loadability limits as shown in Table 2-1. If that occurs the Populations calculate the cost to upgrade the Transmission Agents to the appropriate grade and normalize that by the kWh that will be transmitted through it (C_{UP}). This upgrade cost is included in the C_{GE}.

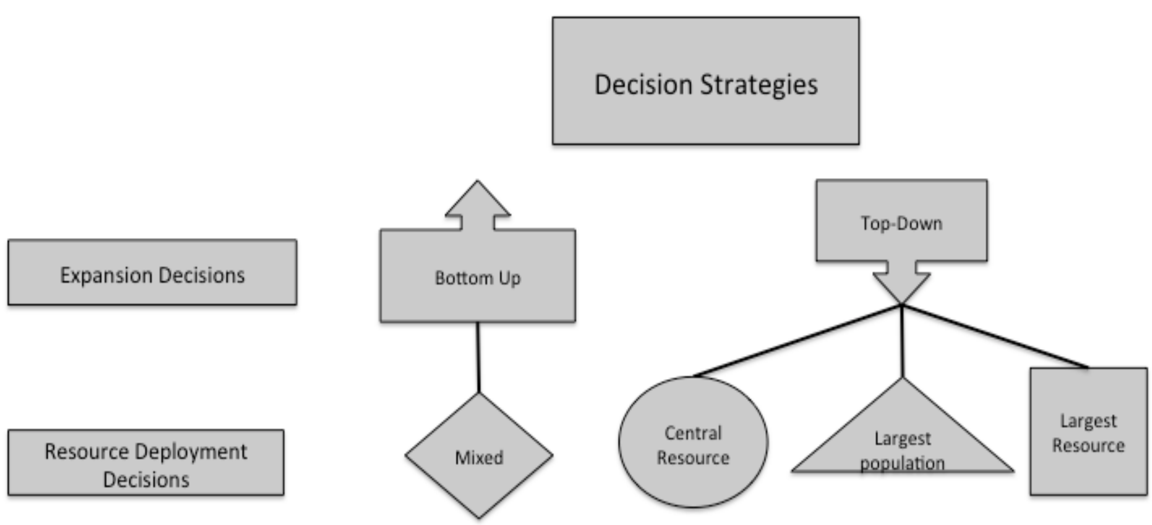


Figure 2-4: Model Scenarios
Four strategies are followed with emphasis on how the expansion of the Distribution System is planned and how the location for deployment of resources is selected.

2.3.3.1 *Bottom-Up Strategy*

In this strategy all Populations report their lowest cost of electrification and whether it corresponds to a C_{GE} or $C_{DG.}$ The Observer chooses the population with the lowest cost for electrification as the next expansion. If the Populations cost corresponds to a C_{GE} the Observer expands the cluster as necessary. If the project cost corresponds to a C_{DG} the Observer creates a Production Unit in the Environment that the Population has identified as least cost. The Observer then connects the chosen Population to the new Production Unit.

In this strategy the Observer is following a participatory approach and making decisions based on the Populations knowledge of the Environment. In a sense this allows Populations to drive the network creation through their identification of cheaper options for electrification. This strategy can be considered as an inclusive planning scheme where local governments and stakeholders can provide input to the process.

A schematic of the Bottom-Up Strategy decision flow can be seen in Figure 2-5.

2.3.3.2 *Top-Down Strategies*

In the Top-Down strategies the Observer follows three resource deployment preferences: Largest Resource, Largest Population, and Central Resource.

Once a resource has been deployed the Observer determines the Population with the lowest C_{GE} for the cluster radiating from the Environment deployed. The Observer disregards Populations that can be electrified more cost effectively through new generation for a later time.

If a time step occurs in which the existing Production Units have no capacity available for expansion or in which all Populations are more economically serviced through new generation the Observer creates a new Production Unit following his preferences. The model progresses adding Production Units, expanding clusters, and creating new clusters as necessary until all populations have been serviced. A schematic of the flow of Top-Down strategies can be seen in Figure 2-6.

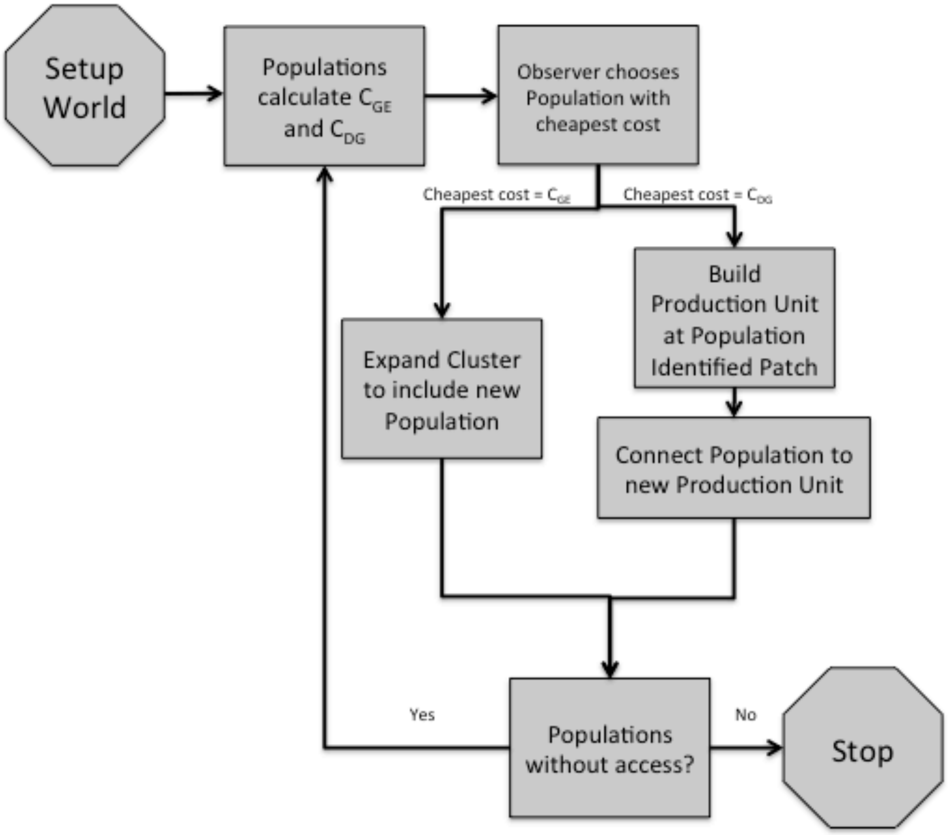


Figure 2-5: Bottom-up strategy model flow

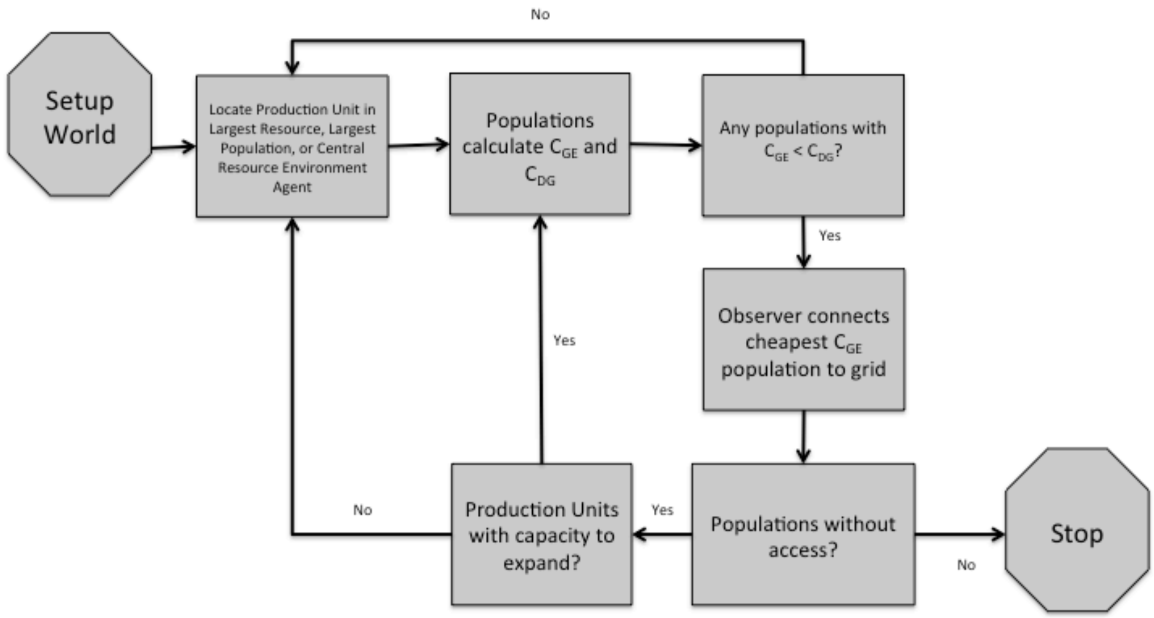


Figure 2-6: Top-Down Strategy model flow

Top-Down Largest Resource

In the Largest Resource strategy, the Observer places a Production Units in the Environment with the largest electricity potential. This is similar to empirical cases where a large resource is used to generate electricity regardless of its distance to populations. The Hoover Dam on the Colorado River is an example. The Observer then creates a Transmission connecting the Production Unit to its nearest Dark Population. The model continues adding the Populations with the lowest C_{GE} until the Cluster is out of capacity. The Observer then places a new Production Unit at the next available Environment with the largest resource.

Largest Population

In the Largest Population strategy, the Observer places a Production Unit in the Environment that results in the cheapest investment to service the Population with the largest number of people. The least cost is considered as the overnight capital cost normalized to the amount of electricity that an Environment can provide. The supporting information contains the equations used by the Observer. Each time step the Population with the lowest C_{GE} is added until there is no more available capacity. The Observer creates a new Production Unit at the Environment that provides the lowest cost for servicing the Population with the largest number of people remaining in the World.

Central Resource

For the Central Resource strategy the Observer finds the Environment with the highest Resource Centrality Index, which the model defines as the level of electricity potential available in an Environment normalized by the distance of that potential to all people in the World. Equations for the RCI are included in the supporting information. Figure 2-7 illustrates the concept of RCI. The Observer places a Production Unit in the Environment with the maximum RCI and connects that Production Unit to the closest Dark Population. Each time step populations with the lowest CGE are added until resources are exhausted. The Observer creates a new Production Unit at the Environment with the largest RCI remaining in the World.

2.3.4 Scenario Simulations

Each scenario is analyzed using the values for the individual variables in Table 2-2. Fifty simulations of each strategy are conducted for each combination of values of the independent variables. This allows the model to take in consideration the stochasticity of the location of populations and power potential and makes the results applicable to general terms and regions.

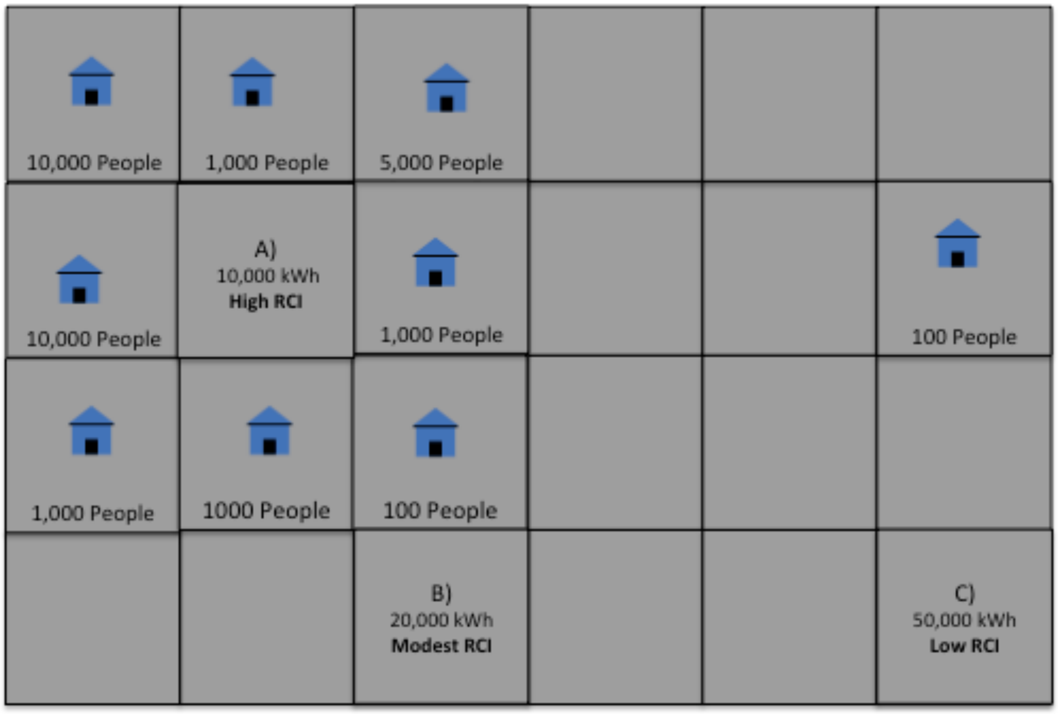


Figure 2-7: Schematic representation of RCI

Environment Agent A has modest electricity potential but is close to several large Populations. Environment Agent B has a lower RCI even though the electricity resources are higher. This is because it is located much further from the larger populations than Agent A. Finally, Environment Agent C has a low RCI despite its high electricity potential. This is because it is furthest away of the three from all the Population Agents.

Table 2-2: Values studied for each parameter

Parameter	Values
Inhabitants (million people)	0.25, 0.5, 1, 5, 10, 50
Peak Demand per person per year (kWh/pr/yr)	100, 500, 1000, 1500
Average Electricity Potential in the World (TWh/yr)	238, 477, 715, 2385

The values for average electricity potential were chosen because they correspond to an average power potential per Environment of 25, 50, 75, and 250 MW respectively.

2.3.5 Distribution System Macro-scale Metrics

Three metrics are used to monitor the macro-scale of the resulting Electricity Distribution Systems. The first is the overnight capital cost of the system infrastructure showing the overall investment that a planner or stakeholder would be facing to establish the Electricity Distribution System. Overnight capital costs are an important factor in situations where capital is constrained and financing is hard to obtain, which often is the case in developing countries.

Because the model assumes a generic power source with homogenous capital and variable costs, the capital cost of the generation equipment is the same for each scenario and each world. Generation costs are therefore not considered in the analysis. The model provides information on which decision strategy minimizes Electricity Distribution System costs for each combination of independent variable values.

The decentralized generation mix, M_{DG}, is calculated by dividing the total number of Clusters by the number of Populations. Each simulation contains fifty Populations. If a simulation results in fifty clusters, each Population has its own Cluster, and the M_{DG} is 1. A simulation with only one cluster results in a M_{DG} of 0.02. This corresponds to a situation where all Populations are connected to a single grid.

The results provided by the model can be organized through the concept of *stress,* defined as the World's total electricity demand divided by its total power potential. High Stress situations are those where the level of power potential in the world is low when compared to the level of overall demand creating a situation where resources are scarce. If renewable electricity potential in the World equals the electricity demand, the resulting stress equals 1. Stress values above 0.75 can be considered high and above 1 can be considered as unfeasible since there are not enough renewable resources to fulfill the demand.

Low Stress situations show high levels of power potential when compared to the levels of demand. Stress levels below 0.75 can be considered as moderate and below 0.5 can be considered low. As an example, most countries in Sub-Saharan Africa have 10-12 times the renewable resources to meet their demand (Deichmann and colleagues 2011). This means that their stress levels are 0.08 to 0.1. Equations for this concept can be seen in the supporting information.

2.4 Results and Discussion

Results obtained from the 50 Worlds are not normally distributed. All figures report median values and the 90% confidence interval.

Figure 2-8 shows the Electricity Distribution System overnight capital cost and M_{DG} for lowest stress simulation, with 2385 TWh/yr electricity resource potential and 0.25 million people.

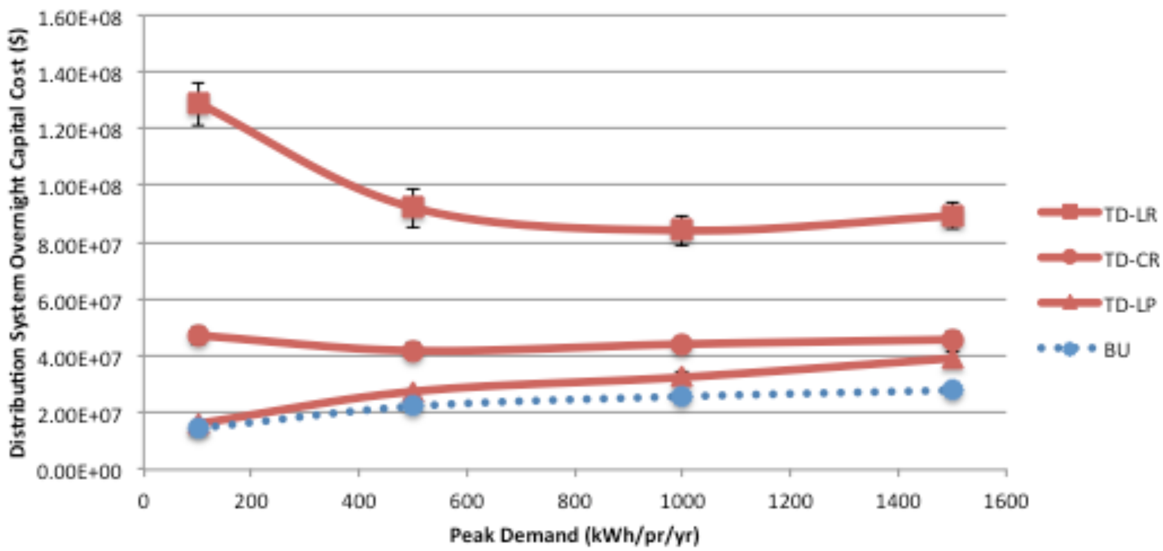
In the lowest stress simulation, the Bottom-Up strategy is economically superior and results in the highest M_{DG}. Higher levels of DG for the Bottom-Up strategy when compared to Top-Down strategies can be expected due to the emphasis on expanding clusters for the Top-Down strategies.

The Largest Resource strategy starts with higher costs at low demand. As demand increases costs are reduced and levelize. In this strategy the Observer insists on using large resources even though the demand is low. The result is an over designed system at low demand levels. A similar situation is seen in the Central Resource strategy although at a much lower scale. The Central Resource strategy seems to remain stable during much of the demand range at these stress levels.

The Largest Population and Bottom-Up strategy outperform the other two strategies. They also show the opposite trend, starting with low costs and rising with demand. This suggests the strategies are better able to size the delivery infrastructure with changing demand. While both strategies increase in cost with demand, the Bottom-Up strategy shows a lower marginal cost increase per demand.

Figure 2-8 also shows that for all strategies as the demand level increases the M_{DG} decreases. This result agrees with earlier studies suggesting that increasing demand makes decentralized generation less economically attractive (Deichmann and colleagues 2011; Levin and Thomas; Parshall and colleagues 2009). It follows that as demand increases the strategies move towards a more centralized structure. Economies of scale in the Transmission are captured as demand increases allowing more Populations to be connected to the same cluster.

Figure 2-9 shows the Distribution System overnight capital costs and M_{DG} for the highest stress simulations, with electricity resource potential of 238 TWh/yr and 50 million people. Costs for all strategies increase rapidly in this situation. This suggests a tipping point is encountered based on stress that causes all strategies to increase in this manner. While the Bottom-Up and Largest Population strategies were the best performers before, here they increase at a higher rate with respect to demand. Central Resource and Largest Resource become more desirable.



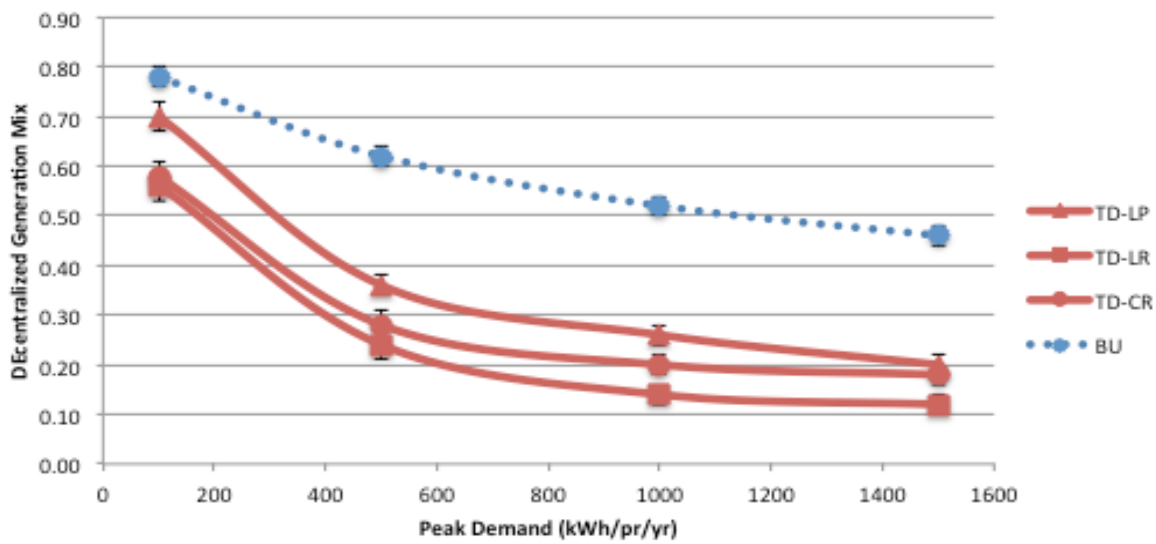


Figure 2-8: Electricity Distribution System overnight capital cost and M_{DG} according to personal demand for a World with 2385 TWh/yr and 0.25 million people

In this stress level the economically superior strategy is the Central Resource. The results presented here suggest that cheaper capital costs for distribution systems could be achieved by locating the production units in more central locations based on the geographic distance to the demand loads even if those demand loads are not considered critical and the resources are not the largest in the region.

Figure 2-9 shows M_{DG} increases with increasing demand. Although this is contrary to studies found in the literature, which state that higher demand results in lower M_{DG}, the available electricity potential may be acting as a constraint. It is likely that the increasing M_{DG} with increasing demand in a high stress World is due to capacity constraints in the Environments. In literature studies the source of electricity for grid extension is usually fossil based and is assumed to increase with demand. This suggests that, with limited resources, a tipping point is reached where the flexibility of the additional electricity potential to create larger capacity clusters and more centralized systems is overpowered by the demand. At that point the system can no longer increase centralization due to the lack of available resources and separate clusters must be created to fulfill electricity demand. Costs rise dramatically after that point.

It is interesting to compare the Low Stress World results in Figure 2-8 to the High Stress World results of Figure 2-9. Increase in per capita demand results in a dramatic increase in cost in the High Stress scenario. Costs are flatter in the Low Stress scenario, and even decrease between the 100-500 kWh/person range for the largest and centralized resource approaches. This may indicate that the larger electricity potential acts as a buffer allowing the increase in demand to be absorbed with lower capital requirements.

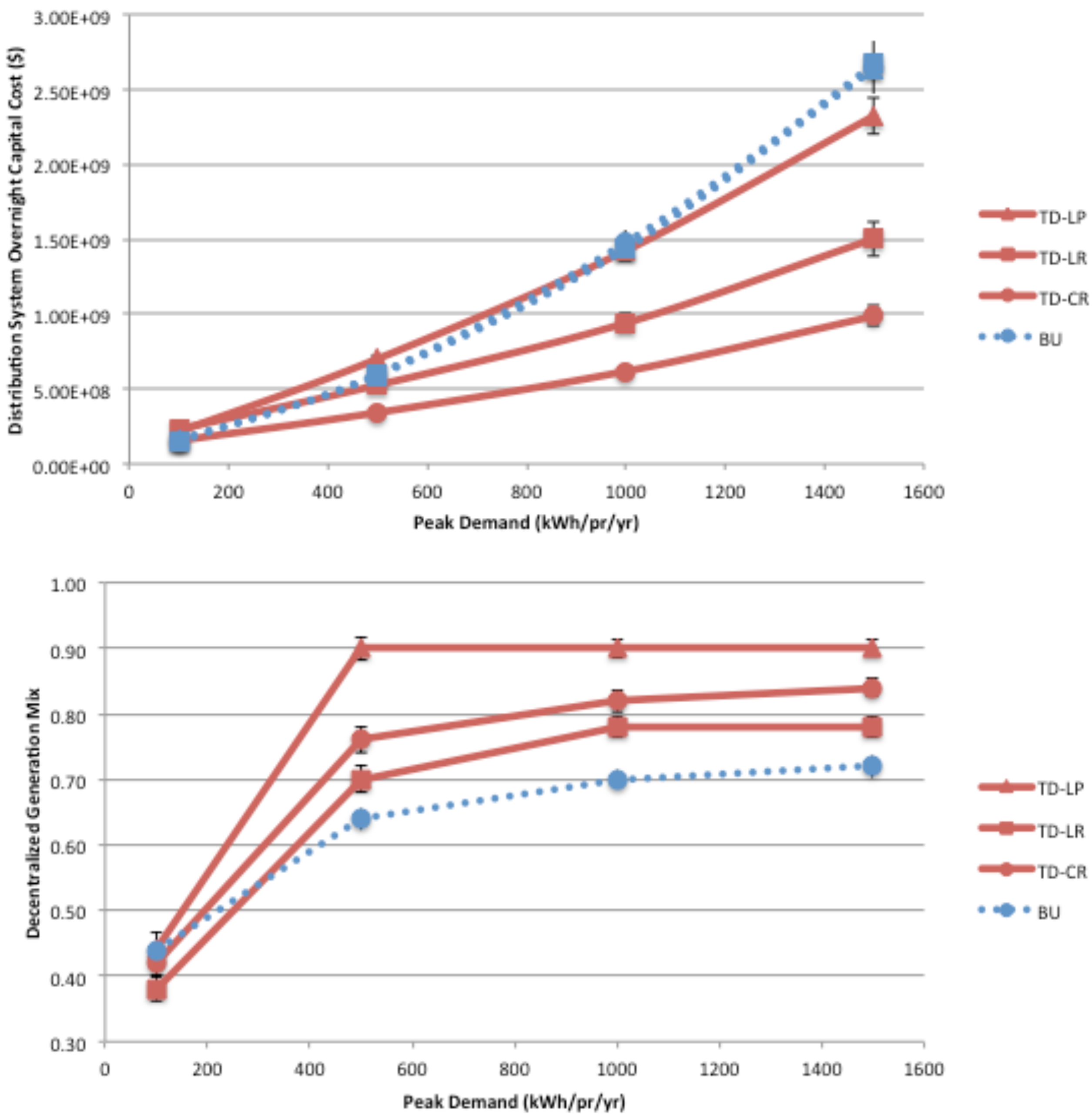


Figure 2-9: Electricity Distribution System overnight capital cost and MDG according to personal demand for a World with 219 GWhr/yr and 50 million people

Figure 2-10 provides example situations in between the two levels of Stress. The Figure shows a World with 10 million people and each frame has increasing electricity potential or reduced stress. The figure corroborates that the increase in potential acts as buffer for capital costs.

Interestingly, the Bottom-Up strategy seems to receive the most benefits out of increases in potential. While the other strategies do decrease in their associated cost the Bottom-Up strategy becomes the economically optimal strategy for a wider level of demand. This suggests that the level of renewable electricity potential in the world can provide an approximation for the demand point or stress level at which Top-Down planning with Central Resources should be replaced for Bottom-Up planning.

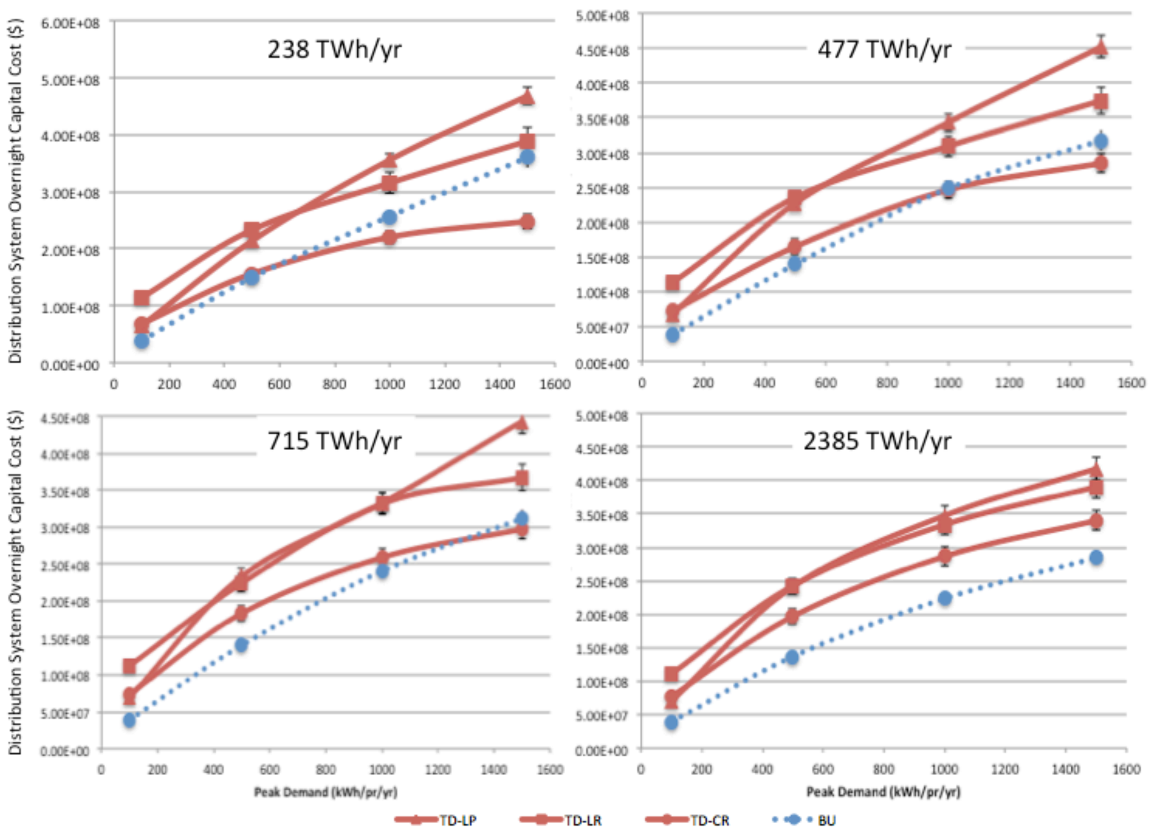


Figure 2-10: Distribution System Overnight Capital Costs in a World with 10 Million people and increasing electricity potential

Higher levels of electricity potential act as a buffer moving the point where the Central Resource strategy becomes economically superior towards higher levels of demand. This means the Bottom-Up strategy is more economical in a wider range of situations with higher electricity potential.

In situations where the resource potential is considerably higher than the demand a more decentralized approach with emphasis on participatory involvement of local governments and DG projects can result in the most economic capital investment for the distribution system. These situations provide central governments with the flexibility to include more stakeholders while still maintaining a lower cost for universal electrification.

In a region where demand is considerable compared to the available resources a centralized planning scheme that emphasizes expansion of grids developed around central resources can result in the most economical infrastructure investment. The deployment of the resources should be tied to their locations in relation to the demand centers and not only on their size or location in relation to the largest or critical loads.

2.5 Conclusions

The paper has shown that an ABM applied to a generalized world can provide significant insights for planning and structuring of new renewable-based electricity delivery systems. This is particularly important for least developed countries where large geographic regions and segments of population lack electricity access but possess large renewable stores. Also, the paper considers the preferences and path dependence of the decisions made by stakeholders, something that is called for in literature (Axtell and colleagues 2002).

The strategies show that when considering limited and geographically bound resources, such as renewables, deploying the largest resource or the resource most economic for large demand centers is not the optimal solution for delivery system costs. Instead a Bottom-Up approach or focusing on Central Resources provides better economic performance.

In general this paper shows that the level of electricity potential available in a region should be compared to the level of demand when formulating decision strategies. The model provides insights on the alternatives for decision management. It shows that as renewable energy availability increases and stress on the system decreases a participatory approach provides opportunities for cost minimization and demographic inclusion. It allows local stakeholders and communities to join in the development of the distribution system. However, when stress levels are high or the resources are significantly limited compared to the demand, central planning and decision-making are key to cost minimization, at the risk of excluding stakeholders form the process. This situation also requires a more detailed inventory of the resources in the region to determine their centrality with respect to the demand centers.

The assumptions of this model must be considered when using it for policy or infrastructure planning. In particular the model assumes that a dispatchable resource is used and that the same resource is available through out the region. Non-dispatchable resources such as solar and wind would have to be modeled with their corresponding fixed and variable costs for proper comparison. Modifying this model to consider the costs of a non-dispatchable renewable energy source, and considering the presence of heterogeneous renewable sources with different fixed and variable costs would strengthen the analysis. The authors intend to develop these changes through the use of case studies of different developing countries in the future.

2.6 Supporting Information for Chapter 2

The following equation is used to calculate the overnight capital cost for delivery systems from Environment Agent *i* to supply Population Agent *j*. This is also used as the calculation for $C_{DG.}$

$$TC_{j-i} = \frac{d_{j-i} * CC_{j-i}}{Q_i} \qquad (1)$$

where:

$TC_{j\text{-}i}$ is the transmission capital cost from Population j to Environment Agent *i* in $/kW

$D_{j\text{-}i}$ is the distance between Population j and Environment Agent *i* in km

$CC_{j\text{-}i}$ is the capital cost of transmission line dependent on the demand of Population *j* and the distance to Environment Agent *i* in $/km as determined by the limits in Table 2-1

Q_i is the electricity potential available in Patch *i* in kWh

The following equation is used for calculating the Resource Centrality Index (RCI) for the central resource strategy

$$RCI_i = \frac{Q_i}{\sum_j \frac{d_{j-i}}{P_j}} \qquad (2)$$

where

RCI_i is the Resource Centrality Index for patch *i* in kW*person/km

P_j is the number of people represented by Population *j*

C_{GE} is calculated through Equation 3.

$$C_{GE}^{jn} = \frac{d_{j-n} * CC_{j-n}}{Q_x} + C_{UP} \qquad (3)$$

where:

C_{GE}^{jn} is the grid extension cost for population *j* to connect to node *n* in $/kWh

d_{j-n} is the distance between population *j* and node *n* in km

CC_{j-n} is the capital cost of transmission line dependent on the demand of Population *j* and the distance to node *n* in $/km as determined by the limits in Table 2-1

Q_x is the electricity potential in kWh still available in the patch occupied by the Power Plant supplying node *n* that has not been to supply other populations

C_{UP} is the cost in $/kW that would be incurred if servicing the new demand results in Transmission Agents connecting the power plant to the new population moving loads higher than those established in Table 2-1.

Equation 4 defines a quantitative value for stress index.

$$\sum_j D_j / \sum_i Q_i \qquad (4)$$

where

D_i is the demand of population *i*

Q_j is the potential in patch *j*

Chapter 3

Satisfying the Rural Residential Demand in Liberia with Decentralized Renewable Energy Schemes

3.1 Abstract

With the lowest access to electricity in the world, the country of Liberia, West Africa, has efforts underway for electrification through a fossil based centralized scheme around its capital city and possible connections to the larger Western Africa Power Pool network. These plans leave a large part of the rural population with no access to electricity.

This work analyzes the potential of decentralized generation to provide electricity to the rural Liberian population. The suppressed demand of the rural population is calculated at 235 GWh/yr. There is sufficient renewable energy potential to supply this demand. The capital costs and electricity prices of decentralized generation with different fuels are calculated and compared to the ability and willingness to pay of rural Liberians.

Small diesel units have the lowest capital cost but photovoltaic, small hydropower and small biomass projects provide lower electricity prices. Biomass and small hydro electricity are affordable for Liberians at $0.08/kWh and $0.11/kWh respectively. Diesel and photovoltaic, with levelized cost of electricity of $0.62/kWh and $0.33/kWh respectively, exceed Liberians' willingness to pay.

Centralized and decentralized electricity development are not mutually exclusive; both may be used within a comprehensive electrification plan. Decentralized generation with emphasis on rural areas can complement the existing plans to achieve the Government of Liberia's goal of universal access to electricity, providing social equity and economic progress. In order to become a reality, rural decentralized electrification will need policy support and focused funding.

3.2 Introduction

3.2.1 Background

After a fourteen-year civil war, Liberia, West Africa, is moving towards redevelopment. With little remaining infrastructure and the lowest level of electrification in the world (Africa Energy Unit 2011), the country seeks to reinvigorate its economy and provide general services to its population. Sub-Saharan Africa has been identified as the biggest challenge for development in the energy sector (International Energy Agency 2010). As Table 3-1 shows, Liberia has the largest electricity tariff and the lowest access to electricity in the region (Africa Energy Unit 2011), highlighting the considerable challenges to electrifying its population.

Table 3-1: Access Rates and Electricity Tariffs in Selected Countries of West Africa

Country	Liberia	Ghana	Ivory Coast	Sub-Saharan Africa	World
Access Rate to Electricity (%)	~1.6%**	60.5	47.3	28.5	79
Rural Access Rate (%)	<2	23	18	11.9	65.1
Urban Access Rate (%)	0.58	85	78	57.5	93.6
Electricity Tariff ($/kWh)	0.43	0.075	0.125		

*Sources: (Africa Energy Unit 2011; International Energy Agency 2010; Levin and Thomas 2012; UNESCO 2009)

**Estimated by authors from source data

A small diesel powered grid is available in the capital city of Monrovia, with electricity tariffs of $0.43/kWh (Africa Energy Unit 2011). Expansion of the centralized grid is under way. Electrification plans include expansion of diesel generating capacity, installation of heavy fuel oil generation, rehabilitation of a large hydro power plant at Mount Coffee, and integration to the Western Africa Power Pool (WAPP) (Africa Energy Unit 2011). Liberia is expected to join the WAPP by the year 2015 through a transmission project between Ivory

Coast, Liberia, Sierra Leone, and Guinea (CLSG), and an additional low voltage connection to Ivory Cost (Africa Energy Unit 2011).

The published electrification plans place emphasis on the urban and industrial sectors in Liberia but raise issues of demographic coverage, reliance on fossil fuels, and dependence on large centralized infrastructure. Centralized, fossil fuel based pathways like the one planned in Liberia, have been shown to create environmental issues, external debt, social divides, and poor quality of service, leaving large segments of the population with no access to electricity (Hiremath and colleagues 2007; Andrade and colleagues 2011). In Liberia, urban areas will receive the majority of the benefits. More than 50% of the rural population in Liberia will remain with no access to electricity by the year 2040 (Africa Energy Unit 2011).

The WAPP projects are key to Liberian electrification and will lower generation costs. Gnansounou et al state that integrating the electricity systems in the region will bring significant benefits through deferred capital investments, increased efficiency, and better reliability (Gnansounou and colleagues 2007). However, the WAPP has been criticized for unrealistic goals and its lack of African ownership and clear objectives. As Pineau notes, the level of integration and functionality to which the WAPP aspires has not been achieved by countries in the European Union or by the United States and the success of the WAPP given the lack of institutional capacity in the region is unlikely (Pineau 2008).

In the published plans, the Africa Energy Unit acknowledges these concerns and calls for efforts that run parallel to central grid and WAPP connections (Africa Energy Unit 2011). The Government of Liberia (GOL) has issued the National Energy Policy (NEP) and the Poverty Reduction Strategy (PRS) outlining a variety of development objectives, including "providing universal access to electricity" (Ministry of Lands Mines and Energy 2009; Republic of Liberia 2008). Further, it has established the Rural Renewable Energy Agency (RREA) to address rural electrification and undertake a National Rural Electrification Master Plan (REMP) (Hamdan 2010; Africa Energy Unit 2011).

Although analyses have been conducted on the economics and feasibility of the centralized grid, little attention has been given to the feasibility of supplying rural demand with renewable, decentralized electricity, which is the focus of this paper. This article quantifies the suppressed electricity demand for the residential sector in rural Liberia and analyzes the possibilities for decentralized electricity generation. The suppressed demand is defined as electricity demand that would be present if service was available. The renewable energy potential in Liberia from different fuels is then estimated and an economic analysis of decentralized generation (DG) through these fuels is conducted. Solar photovoltaic (PV), small hydro, and biomass direct combustion are used as the feasible fuels in Liberia. Wind power is ignored due to low wind speeds throughout the country (NASA 2011). For comparison, the economics of small diesel fuel generation are presented due to its current use in rural areas of Liberia. The economic analysis includes overnight capital costs and simplified calculations of resulting levelized cost of electricity (LCOE). These costs are compared to the ability and willingness to pay of rural Liberians. Finally, tradeoffs of the fuel options are presented.

3.2.2 Reaching Rural Populations in Liberia

Grid expansion (GE) and decentralized generation (DG) are two methods that can be used to reach rural electrification goals. GE extends the centralized generation capacity by creating transmission and distribution networks to rural populations. DG uses smaller generation units located close to the rural load centers, avoiding large distribution networks. DG may involve the use of micro-grids joining a few communities or load centers and may eventually be connected to a larger grid.

Due to the current electrification plans in Liberia and the lack of existing centralized infrastructure, this paper places emphasis on DG for rural areas. DG is more economical than GE in situations with low population density, low electricity demand per person, lack of centralized generation infrastructure, and difficult terrain (Van Hoesen and Letendre 2010; Abanda 2012; Africa Energy Unit 2011; International Energy Agency 2010). Zerriffi and Wilson point out that the scalability of DG is particularly well suited for the low demand and sparse population of rural areas (Zerriffi and Wilson 2010). Further, Levin and Thomas use an algorithm to determine the optimum economic choice between DG and GE for each load center in a series of countries (Levin and Thomas 2012). When the algorithm is applied to Liberia, DG is more economical for 72-77% of the population and 95-98% of the load centers (Levin and Thomas 2012). This distribution reflects the urban and rural demographics of Liberia, with the capital city of Monrovia being the only truly urban center and holding around 28% of the population (Republic of Liberia 2009).

3.2.3 Available Renewable Energy Resources in Liberia

The solar potential in Liberia is strong throughout the country. No direct measurements of insolation are available, but satellite data establishes horizontal surface insolation at 208.5 W/m^2 (Africa Energy Unit 2011).

Liberia has rainfall in the range of 1600 - 4000 mm/yr (Milbrandt 2009; Hamdan 2010). Studies have shown that medium hydro projects have a potential of over 400 MW on the Cavalla and Tiboto Rivers alone (Ministry of Lands Mines and Energy 2007). These rivers require bilateral cooperation with Ivory Coast and Sierra Leone, but 24 other possible sites have been identified for small to medium hydropower (Africa Energy Unit 2011). There are also opportunities for micro and pico hydro projects.

Although more than 99% of the population of Liberia depend on charcoal for cooking and heating needs, significant amounts of biomass residues are available that would not hinder the production of traditional fuels or food. Electricity production depends on conversion efficiency of the technology used, which can range from 20-40%, but a study by the National Renewable Energy Laboratory assumes 1 to 2 GWh of electricity per tone of biomass (Milbrandt 2009). This paper considers only food and cash crop waste, although other sources of biomass are available. Milbrandt estimates the present potential of these residues at 5,121 GWh/yr (Milbrandt 2009).

3.3 Methods

3.3.1 Estimating Demand

The Liberian electrification situation is particularly novel. Historical data is often a key component of electricity forecasts. Due to the drastic and disruptive impact of the civil war, historic data are not useful to project econometric values, energy use, and demographic trends. Liberian rural residential electricity demand is estimated in this paper using population growth, yearly increase in connections (or increase in access to electricity), and increase in demand from people already receiving electricity. These are the same drivers used by the World Bank for urban residential areas in Liberia (Africa Energy Unit 2011), but are modified with data specific to the rural areas. The model begins with current data and creates a forecast of demand in the year 2050 with Equations 1-4.

A computer programming software called Netlogo is used for the model. Netlogo is common in Agent Based Modeling applications (ABM) (Wilensky 1999), but its ability to create stochastic scenarios makes it a good tool for this work. Utilizing the "BehaviorSpace" tool included in the software allows users to perform thousands of experiments in short periods of time and easily creates Monte Carlo simulations.

$$D_{T0} = D_R * AR_0 * P_0 \qquad (1)$$

Where

D_{T0} = Total initial demand

D_R = Typical demand in rural areas per person

AR_0 = Initial rural electricity access rate in percentage

P_0 = initial population

Each time step of the model the total demand becomes

$$D_{Ti} = D_R * AR_i * P_i + D_{Ti-1} R\% \qquad (2)$$

Where

D_{Ti} = Total demand in year i

AR_i = rural electricity access rate in year i

P_i = Population in year i

$R\%$ = yearly rebound %

and

$$AR_i = AR_{i-1} * (1 + AR_{inc}) \qquad (3)$$

$$P_i = P_{i-1} * P_{inc} \qquad (4)$$

where

AR_{inc} = yearly percent increase in rural electricity access

P_{inc} = annual percent population growth

The software also provides an intuitive graphic user interface, and an easy installation package for possible new users. Netlogo makes it easy to monitor parameters and makes clear to users the variables involved in the analysis. A screen shot of the model can be seen in the Supporting Information.

A Monte Carlo simulation is performed with the BehaviorSpace tool. Two thousand experiments are conducted to determine the expected results of electricity demand, capital costs, levelized electricity prices, and total rural population served. The parameter ranges presented in Table 3-2 were used to create triangular distributions with a mode equal to the mean of the parameter range. This approximation was chosen due to the scarcity of data. For each experiment, the model stochastically chooses a value from the distributions to perform the calculations.

Table 3-2: Parameters for estimate of demand

Parameter	Upper Limit	Average	Lower Limit	Sources
Yearly Population Increase (%)		2.8		(united Nations, 2011)
Increase in access to electricity (%)	2	1.5	1	Assumed
Increase in electricity demand by electrified populations	2	1.5	1	(Africa Energy Unit; International Energy Agency)*
Electricity Demand	60	50	40	(International Energy Agency)*

*Source provides average value; upper and lower limits are defined as +/- 20% of the average

Parameter data comes from Liberian census and world estimates of rural electricity demand. The latest Liberian census indicated that 2.5 million people lived outside of the greater Monrovia area in 2008 (Republic of Liberia 2009). These values are used as the initial parameters in the model. Liberian population has increased at a rate of 2.8% over the past five years (United Nations 2011), and is assumed to continue at this rate throughout the study period to year 2050. The increase in demand is estimated at 1.5% according to assumptions made by the World Bank in their recent studies of the Liberian urban case (Africa Energy Unit 2011). Average demand of electricity per person in rural populations is estimated at 50 kWh/yr. This value is typical in cases similar to Liberia's (International Energy Agency 2010) and is conservatively high when compared to other studies in developing countries (Buchholz and Da Silva 2010; Deichmann and colleagues 2011; Levin and Thomas 2012).

Since increase in access to electricity can largely depend on policies and available investment, the paper assumes a range of 1% - 2%. This ensures that over 50% of the rural population is reached, capturing the population not serviced by the central grid plan.

3.3.2 Estimating Capital Costs

Overnight capital costs ignore the time lag of constructing a project and place the cost in present time. Here they are calculated using world averages for the different technologies. Although world averages are only a proxy, data collected from biomass and small hydro pilot projects currently under way in Liberia shows that costs are in line with world averages for those technologies (Winrock International 2011a; Africa Energy Unit 2011; Winrock International 2011b). For PV projects, conversations with suppliers in Liberia suggest capital costs can be 60% higher than world averages when purchasing individual components from a retailer (Union Strong Company, personal communication, 08/2012). This paper assumes that a public or private solar PV project of larger scale would encounter values more in line with world averages.

Transmission, distribution, and home connections are expected to be similar for all technologies and are not included in the capital cost calculations. Equation 5 is used to calculate the capital costs of biomass, small hydro, and small diesel generation.

$$C_i = \frac{D_T * CC_i}{8766hr * DF_i} \qquad (5)$$

Where

C_i = capital cost of technology i (for hydro, biomass, and diesel)

D_T = total electricity demand for rural areas in kW

CC_i = unit capital cost for technology i in $/kW

DF_i = duty factor (actual output compared to nameplate capacity) for technology i

In the case of solar PV technology capital costs do not include a duty factor but depend on insolation values. Also, unit capital costs are given in \$/Wp, a metric that includes the efficiency of the panels. Solar capital cost then becomes:

$$C_S = \frac{D_{Ti} * 1000(W/m^2) * CC_S}{I * 8766hr} \quad (6)$$

Where

C_S = capital cost for solar PV

CC_S = unit capital cost for solar PV in \$/kWp

I = insolation in Liberia in W/m^2

3.3.3 Estimating Price of Electricity

For each technology, a levelized cost of electricity is calculated including capital costs, fixed operation and maintenance costs, variable costs (fuel), and duty factors. The calculations in this paper represent a simple analysis of this metric. Equation 7 is used for the calculation and Tables 3-2 and 3-3 are a summary of the data and sources for the calculations.

$$P_{ei} = \frac{CRF_{eff} * CC_i}{8766hr * DF_i} + HR_i * P_f^* + O \& M_i \quad (7)$$

Where

P_{ei} = levelized price of electricity of technology i in \$/kWh

CRF_{eff} = effective capital recovery factor including taxes and insurance

$$CRF_{eff} = \frac{d}{\left[1-(1+d)^{-n}\right]} + T \& I$$

d = discount factor

n = operational life of unit (15 years for solar PV and 30 for all other technologies)

$T \& I$ = taxes and insurance

HR_i = heat rate of fuel for technology i in Btu/kWh

P_f^* = levelized prive of fuel $= \frac{d}{d-j} * P_f$

P_f = price of fuel in \$/Btu

j = price levelizer assumed at 2%

$O \& M$ = operation and maintenance cost of technology i in \$/kWh

Sensitivity analyses are conducted through one at a time perturbation of the parameters in the model. Parameters are changed by +/-20% from their mean. This sensitivity analysis shows the parameters where uncertainty is most likely to create a large deviation from the calculated results.

3.3.4 Gathering Renewable Energy Potential Data

Biomass potential in Liberia is presented in the report published by (Milbrandt 2009). Small hydro potential is estimated by utilizing only the small sites mentioned above. A 40% duty factor for these projects is assumed. An efficiency of 10% and an insolation of 208.5 W/m^2 are used for PV projects (Africa Energy Unit 2011). The model assumes the use of 0.01% of the Liberian area for PV production, around 10 km^2, with an average of 6 hr/day of sunshine (NASA 2011).

3.3.5 Estimating Ability to Pay Monthly Electricity Bills

Winrock International conducted a survey on a small sample of the population in Liberia (Winrock International 2011a). The survey results are used here for determination of expected monthly electricity bills and customers' ability and willingness to pay. This survey is the only available study in the literature that examines these parameters for the Liberian rural case.

The survey sample comes from a relatively populated area in Bong County, near a mini-hydro pilot project. Residential customers, small businesses, and a few large institutions are included in the sample. The results of the Winrock surveys shows the high costs of electricity options and the available commercial demand that can help justify larger generation schemes like the micro-hydro project being funded by USAID (Winrock International 2011a, 2011b).

According to answers provided by the residential customers, the ability and willingness to pay of Liberian households is \$10/month (Winrock International 2011a). This is lower than the actual fuel expenditures of Liberians. The survey shows that households spend an average of \$13 per month on lighting alone. Liberians use high costs options such as kerosene lamps (\$1.53/kWh), car batteries (\$8.43/kWh), dry cell batteries (\$74.01/kWh), candles (\$8.27/kWh), and household diesel generators (\$3.96/kWh) (Africa Energy Unit 2011).

Winrock's survey found that the average household in this particular area has 8.7 people, higher than the national average of 5 (Republic of Liberia 2009). This translates to a yearly demand of 435 kWh/household when using an average demand of 50 kWh/pr/yr. Prices of electricity determined with Equation 7 are used to determine the monthly bill of a household connected to each technology.

Table 3-3: Parameters for Cost and Levelized Price of Electricity Calculations

Parameter	Upper Limit	Average	Lower Limit	Sources
Solar PV				
Solar Capital Costs ($/kWp)	4100	3400	2700	(International Energy Agency 2011)
Solar O&M ($/kW)	14.02	11.68	9.34	(International Energy Agency 2011)*
Insolation (W/m^2)	250	208.5	167	(Africa Energy Unit 2011)
Small Hydro				
Hydro Capital Cost ($/kW)	2400	2000	1600	(Paish 2002; Africa Energy Unit 2011)
Hydro O&M ($/kWh)	0.04	0.025	0.01	(International Energy Agency 2011)
Hydro Duty Factor (%)	60	40	20	(International Energy Agency 2011)*
Small Biomass				
Biomass Capital Cost ($/kW)	4100	3350	2600	(International Energy Agency 2011)
Biomass O&M ($/kW)	77.34	64.45	51.6	(EPA 2010)*
Biomass Fuel Costs ($/ton)	3	2	1	(Schmall and Williams 2011) Source provided an average, authors create 50% limits around it
Biomass Duty Factor (%)	90	80	70	Assumed
Biomass Heat Rate	19	17.5	16	(Scurlock 2001; Milbrandt 2009)
Small Diesel				
Fossil Capital Cost ($/kW)	720	600	480	(Foster and Steinbuks 2009)
Fossil O&M Cost ($/kWh)	0.024	0.02	0.016	Assumed after review of HOMER Micropower Optimization community website (Anon 2012)
Fossil Fuel Consumption (gal/kWh)	0.143	0.119	0.095	(Foster and Steinbuks 2009)*
Fossil Fuel Costs ($/gal)	4.80	4.00	3.20	Authors' observations in Liberia
Fossil Duty Factor (%)	90	80	70	Assumed

*Source provides average value; upper and lower limits are defined as +/- 20% of the average

3.4 Results and Discussion

3.4.1 Main Results

The estimated Liberian demand for rural residential electricity in 2050 is 235±75 GWh/yr to service 61±33% of the rural population's total demand. This exceeds the level needed to complement the existing electrification programs and achieve the universal electrification goal of the GOL. A similar level of electricity consumption would power around 6,800 U.S. households (World Bank 2013; Lofquist and colleagues 2010).

Table 3-4 compares the estimated demand to the available renewable energy potential. The solar and biomass potentials in Liberia are large enough to supply the expected demand. These technologies are particularly useful since their location can be planned near the load centers for decentralized schemes. Small hydro can cover more than 98% of the expected demand. Hydropower presents the logistical constraint of having fixed geographical location.

Table 3-4: Estimated Electricity Demand in 2050 and Renewable Energy Potential in Liberia

Liberian Electricity Demand by year 2050 (GWh/yr)	Small Hydro Potential (GWh/yr)	Solar PV Potential (GWh/yr)	Biomass Potential (GWh/yr)
235±75	231	457	5121

The overnight capital costs calculated in Equations 5 and 6 can be seen in Figure 3-1. These are the costs that would be incurred to fulfill the estimated demand by using each technology exclusively. Although a combination of technology options is more likely, Figure 3-1 provides cornerstone scenarios for the total amount of capital investment Liberia would need to provide their rural population with electricity in a decentralized scheme. Further, it shows a relative cost comparison for the Liberian renewable energy options.

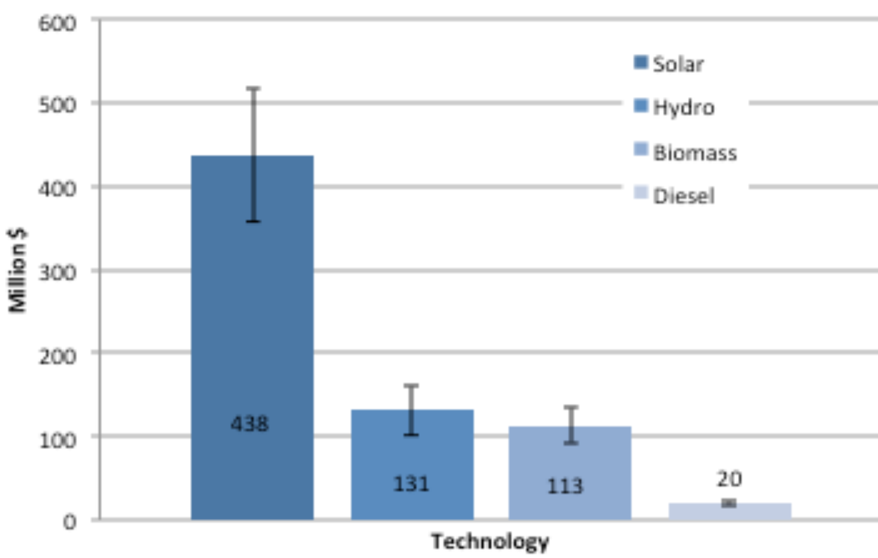


Figure 3-1: Overnight Capital Cost to Fulfill Expected Demand in 2050

Figure 3-1 shows that renewable energy technologies involve a significantly larger capital investment when compared to diesel. However, the technologies should also be compared on the grounds of resulting electricity tariffs, or levelized cost of electricity (LCOE). LCOE normalize fixed and variable costs of a project with the lifetime energy output of the project, i.e. $/kWh. For solar PV the lifetime of the project is estimated at 15 years to reflect the expected life of solar components. All other technologies have an assumed lifespan of 30 years.

LCOE provides a broader picture for decision makers when compared to overnight capital costs. Stakeholders can consider both metrics to pursue an appropriate technology. When considering this broader picture all of the renewable technologies are more affordable than the diesel option. Expected levelized costs of electricity (LCOE) can be seen in Figure 3-2. Model results for LCOE can be validated with recent world averages developed by the International Renewable Energy Agency (IRENA). Solar PV systems, with storage included, have a LCOE in the range of $0.36/kWh - $0.71/kWh for systems of less than 5 kW of installed capacity (IRENA 2012b). Larger systems achieve costs as low as $0.26/kWh (IRENA 2012b). The model results of $0.33/kWh are plausible given the paper's assumption of purchasing components in bulk for community size projects. For small hydro projects, model results of $0.11/kWh agree with IRENA's empirical data of $0.02/kWh - $0.10/kWh, with pico schemes as high as $0.27/kWh (IRENA 2012a). For biomass boilers and gasifier technologies, IRENA provides a range of $0.06/kWh - $0.24/kWh. The model's result of $0.08/kWh is at the low end of the range provided. However, IRENA finds lower costs where local food and cash crop wastes are readily available as feedstock, which is the situation in this analysis (IRENA 2012c).

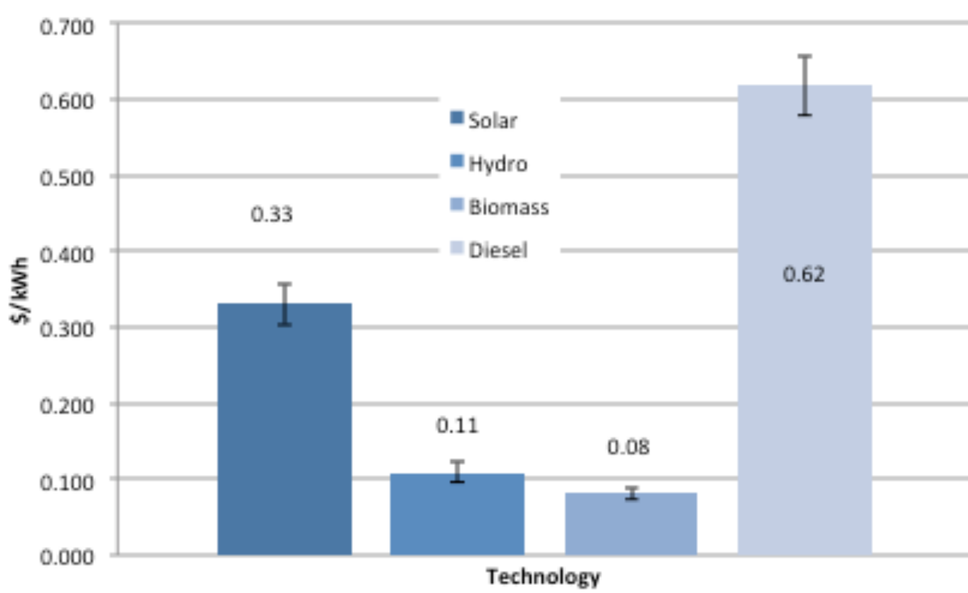


Figure 3-2: Levelized prices of electricity

Figure 3-3 shows the cost of a consumer's monthly bill under each technology. The costs of biomass and small hydro electricity are below Liberian willingness to pay of $10 per month. Biomass and small hydro electricity prices are also lower than the tariff for electricity from the centralized grid present in Monrovia and the best-case scenario calculated by the African Energy Unit for the expansion of that grid of $0.12/kWh (Africa Energy Unit 2011). PV is not explicitly under the willingness to pay of the Liberian sample population but it is affordable compared to the present expenditures of Liberians for lighting services of $13 per month.

All three renewable technologies provide monthly bills in line with reported acceptable costs. Winrock expects a 50W connection to the pilot micro-hydro project to charge $6 per month and a 100W connection $13 per month (Winrock International 2011b). Diesel generation does not appear to be affordable for Liberian consumers since monthly bills would be more than 100% higher than the stated willingness to pay of consumers in the Gbanga region.

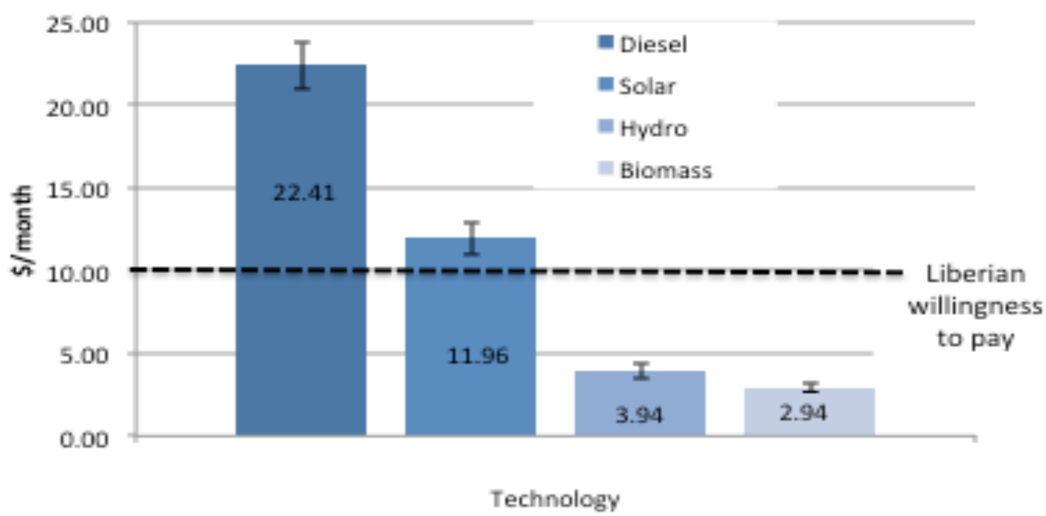


Figure 3-3: Monthly Costs of Electricity For Each Technology

3.4.2 Sensitivity Analysis

One at a time perturbation of parameters allows the identification of areas of sensitivity in the model. Particular attention is paid to significant correlations that affect the main results of the work; total expected electricity demand, total expected capital costs, and LCOE.

Total expected electricity demand has a strong direct correlation with population growth and average household demand. A change of 20% in population growth causes a change in total electricity demand of almost 25%. A change of 20% in household demand causes 20% change in demand. Increase in consumption of connected populations does not significantly affect the results.

Total expected capital costs of each technology have a strong indirect correlation to duty factors (insolation in the case of PV). When technologies operate at a lower duty factor a greater installed capacity is required to fulfill the demand. Duty factors also cause the greatest change in LCOE for all technologies. A decrease in duty factor means that less electricity is being produced each year and the total fixed cost of the project is normalized to a lower number of energy units produced.

As expected, changes in technology capital costs per kW have a direct correlation to LCOE. However, the change is less than 1:1.

Hydropower costs show significant sensitivity to duty factors. Decision makers should be aware that climatic events could highly influence the electricity prices for this technology. For example, a reduction in river flow would impact the duty factor of the technology increasing electricity prices.

Biomass technologies display stable electricity prices. A wide range of feedstocks is available in Liberia, making it easier for biomass projects to maintain stable supply and costs. Changes in heat rate and feedstock prices do not significantly change the tariffs calculated. Although the LCOE is sensitive to duty factor, it is easier to control this parameter with biomass technology as long as there is demand. Crops can be stored with appropriate techniques for later use in electricity production, allowing inventory management and on-demand generation.

Diesel LCOE shows a direct correlation with fuel consumption. A 20% change in fuel consumption causes a 19% change in electricity prices. Generation units of lower quality and fuel efficiency would increase the already high LCOE of diesel. This result agrees with the fact that the largest share of diesel costs come from fuel prices.

Graphs for each group of parameters evaluated during the sensitivity analysis can be found in the Supporting Information.

3.4.3 Fuel Accessibility

Fuel supply logistics are key in electrification. In the case of fossil fuels, Liberia lacks sufficient infrastructure to import, store, and transport fuels (Africa Energy Unit 2011; World Bank 2010). Transporting diesel for electricity production would increase prices and add pressure to the transportation system.

Renewables on the other hand, have the benefit of being located close to the point of use. Solar insolation is high throughout the country. However, transportation of solar panels and other equipment related to solar PV projects would add significant cost to an already expensive technology.

Hydro projects can generally be placed near load centers. Turbines and other parts can be created locally if the technology and knowledge is appropriately transferred (Paish 2002). This allows for small hydro projects to avoid the logistical issues involved with transportation.

Biomass residues are already located in areas of potential electricity loads. Liberia's soil, climate, and fallow arable land allows for easy location of coupled farming and electricity production projects. However, the residues are scattered in fields and must be collected and transported to a generation site. Collection efforts should be planned appropriately with farmers and communities to avoid price increases.

3.4.4 Intermittency of Renewables

Electric projects need to be reliable for communities to achieve full benefits. A study by Kooijman-van Dijk shows that blackouts affect the uptake of electricity and increase the problems faced by enterprises that adopt it (Kooijman-van Dijk 2012a). Predictability of blackouts allows enterprises to adapt to the supply (Kooijman-van Dijk 2012a). Renewable energy projects with insufficient or intermittent supply should provide transparency to their customers communicating hours of operation and expected black outs. An example of a proper arrangement is the micro-utility that services a market in Bangladesh. This utility proved successful by using a five hour per day arrangement (Ibrahim and colleagues 2002). Alternatively, more than one technology can be used. A Solar PV array could have a back-up thermal generator, whether fossil or biomass based. Hybrid systems for continuous supply are a promising way of leveraging the advantages of each technology while keeping capital costs and user tariffs low. (Mondal and Denich 2010) finds that in Bangladesh hybrid systems using PV and diesel generation together form the only economically feasible option for the region studied.

Storage solutions can also be pursued to enhance the performance of renewables and availability of electricity. Batteries are widely used in Liberia to store power created by diesel generators. Examples are available in developing countries where deep cycle and car batteries are used to provide electricity to households. Batteries are charged at a central location in the community and each family transports it back to their homes for use. This practice has even been used to model economic performance of generation projects (Buchholz and Da Silva 2010).

Connecting renewable energy projects in remote areas to the grid can also form a hybrid system. A transmission line that connects a DG project to the closest section of the grid can allow the grid to act as a storage device through a net metering program. The grid can buy energy from the renewable project during peak hours but sell electricity to the project when renewable energy may not be available. The electricity produced during peak hours by the renewable projects can help alleviate supply constraints on grid. This set up was modeled for a system in a remote island in India. The availability of the grid as a back up and storage device made the renewable energy projects financially viable while providing extra electricity supply to a grid with high demand (Karki and colleagues 2008).

3.4.5 Comparative Summary

Table 3-5 offers a comparative analysis of each technology. Although biomass has a high technology capital cost per kW relative to the other technologies, it affords the cheapest LCOE for the users and is a stable source of electricity generation. Because of its performance, the total investment to supply all of Liberia's modeled demand is the cheapest of the renewable energy options as seen in Figure 3-1. The stability of its electricity prices and duty factors allows generators to create appropriate forecasts for a clear fee-for-service approach with lower uncertainty.

Table 3-5: Comparative Analysis of Decentralized Generation Technologies

Generation Technology	Diesel	Solar	Hydro	Biomass
Average Capital Cost	$720/kW	$3400/kWp	$2000/kW	$3350/kW
Levelized Electricity Price ($/kWh)	0.62	0.33	0.11	$0.08
Stability of Electricity Price	Highly variable particularly due to fuel consumption	Variable due to climate conditions	Variable due to climate conditions	Stable due to flexibility of fuel and heat rates
Duty Factor	Stable	Variable	Variable	Stable
Fuel Access	Complicated in rural areas due to little road infrastructure	Simple	Limited to potential locations close to loads	Variable, fuels already close to loads but must be collected from fields
Maintenance Capacity	Available	Lacking	Available	Available
Susceptibility to Intermittency	Low	High	Medium	Low

Biomass fuel availability is good in Liberia and located near load points. Because electricity prices for this technology are stable with regards to the energy content or heat rate of the fuel, different cash and food crop residues already on the ground can be utilized avoiding a competition with food supply. The large amount of fallow agricultural land in Liberia allows for careful planning of combined food and energy projects if desired. The situation in Liberia is consistent with results that find that Africa and Latin America have superfluous land to meet the energy requirements of their populations even when forested lands are taken out of the equation (Rahman and colleagues 2014).

The use of residues represents an income opportunity for farmers and rural communities. Agriculture is considered one of the keys to sustainable development in Liberia and more than 70% of the population depends on it for their income (Republic of Liberia 2008; Milbrandt 2009). It may also create a separate market for non-traditional agricultural products.

Biomass is a better economic driver when compared to other electrification projects. In Uganda, biomass projects create four times the economic flows within the community when compared to small diesel, grid connected hydro, and solar panels (Buchholz and Da Silva 2010). This evidence is supported also by experiences with projects in India (Dasappa and colleagues 2011).

The technical and human capacity in the country should be considered when deciding on electrification technologies. Diesel generators are common in Liberia and the knowledge necessary for their maintenance is available. The level of knowledge required for PV technologies is lacking. Hydro and biomass technologies are more mature and their maintenance is similar to diesel and other applications present in Liberia. This makes them less susceptible to the lack of human capacity for their service and operation.

3.4.6 Decentralized Electricity as an Economic Development Tool

It is well documented that DG provides economic, social, and environmental benefits in rural areas, moving populations out of poverty, creating wealth, protecting the environment, and catalyzing development (Andrade and colleagues 2011; van Els and colleagues 2012; Cook 2011; Kooijman-van Dijk 2012a; Gómez and Silveira 2012). But to achieve sustainable development, other components must be present. (Welle-Strand and colleagues 2011) analyses the experience of the Norwegian Aid program in the energy sector of developing countries and concludes that while electricity is necessary for development, it is not sufficient and investment in other infrastructures is required alongside electrification efforts. (Wolde-Rufael 2009) states that in 11 out of 17 African countries studied electricity consumption was only a contributing factor to growth. Their results identify capital and labor as more important for increases in economic production. Similar results were obtained by (Apergis and Payne 2009) in six Central American countries where an increase in labor force was more important than energy consumption in gross domestic product growth.

Because of this some countries, such as Cuba have created efforts that include electrification inside a more general development agenda (Cherni and Hill 2009). The question remains on how to identify the priorities for development in different countries. (Karakosta and Askounis 2010) uses a linguistic approach to enhance the technology needs assessment and characterize the priorities for energy improvements in developing countries. They find that providing electricity to households is among top priorities in countries like Israel, Kenya, Chile, and China. They also find that where electricity distribution is not well-established electricity for households appears as a top priority. This emphasis is not present in countries with good electricity distribution systems and good household accessibility pointing to the importance of electricity for the residential sector in developing countries.

After the war Liberia created a Poverty Reduction Strategy (PRS) with four reinforcing pillars, expanding peace and security, revitalizing the economy, strengthening the rule of law, and rehabilitating infrastructure and delivering basic services (Republic of Liberia 2008). Electricity supply applies directly to three of those pillars. Further, ensuring electrification of rural populations is key in reducing inequality in the country as expressed in the PRS. Liberians identified the rebuilding of roads as the number one development need during PRS consultation meetings. Roads were viewed as essential for improvements in education, access to health care, better governance, and revitalization of agriculture (Republic of Liberia 2008). However, the electrification of rural areas is still a necessary condition for improvements in many of these development goals and others such as the millennium development goals.

Because of this, investment in electrification and ensuring that rural and urban areas receive equal opportunities for electricity services can be viewed as an opportunity for accelerating development. Examples of the use of electricity and particularly rural electrification schemes as catalysts for economic growth and prosperity are present around the world. In Bangladesh and Nepal the establishment of cooperatives for rural electrification resulted in other services for the communities like micro-finance and technical training (Yadoo and Cruickshank 2010). Statistical analysis of the Liberian situation suggests that the economy is driven by labor, petroleum, electricity and capital (Wesseh and colleagues 2013). But the analysis also shows that electricity can be a substitute for petroleum allowing Liberia to pursue electrification as a major piece of economic development.

Renewable energy schemes in particular can be used to build capacity and economic activity in the country. Local industries have been created out of rural electrification projects. For example, turbine designs from German and Swiss aid projects were transferred successfully to Peru, Sri Lanka, Nepal and Indonesia where local manufacturers and workshops took on the business (Paish 2002). This is particularly useful in Liberia where the lack of technical knowledge represents a good opportunity for development organizations to provide vocational training, new job opportunities, economic activity, and electric supply.

3.4.7 Financing Projects

Recent literature suggests that successful approaches to rural electrification often require subsidizing of the capital equipment by donor agencies or the national government (Cook 2011; Africa Energy Unit 2011; Ilskog and colleagues 2005). A combination of subsidies, grants, and cost recovery through fee-for-service schemes can be used. In South Africa, several fee-for-service solar power concessions have thrived using these methods, even in the face of uncertain government subsidies and encroachment by the national utility through grid connections in the concession areas (Lemaire 2011). A similar approach in Zambia has resulted in successful rural electrification companies (Lemaire 2009).

Renewable energy projects can also be financed through mechanisms available for climate change mitigation. The Clean Development Mechanism (CDM) established by the United Nations provides a vehicle for developing countries to receive financing from developed countries for projects that can reduce carbon emissions that would occur without the aid (United Nations Framework Convention on Climate Change 2012). This makes capital recovery and financing easier for both public and private enterprises.

Civil societies can take advantage of climate mitigation schemes as well. For example, a community cooperative or non-government organization can use the Global Environmental Facility Small Grants Programme (Global Environment Facility 2012). This program allows the community groups to establish a project of up to $50,000. Given the average values in 3-2 for small biomass, a community can afford up to 15 kW of biomass production or 65 MWh/yr of electricity assuming a duty factor of 0.50. A typical village cluster in Uganda of 250 households, several small businesses, a school, and medical center consume close to 20 MWh/yr (Buchholz and Da Silva 2010). Examples of such grass roots cooperatives have been successful in Tanzania and Costa Rica (Ilskog and colleagues 2005; Kirubi and colleagues 2009).

3.4.8 Industrial Loads

This paper does not include the commercial and industrial loads in rural Liberia. Several concessions for mining, rubber, palm oil and logging are present or expected in the near future and have been taken in consideration in the centralized grid plan (Africa Energy Unit 2011). In developing countries, these companies usually pursue self-generation of power, even when a utility is present, due to the instability of electricity generation (Foster and Steinbuks 2009; van Kooten and colleagues 2010).

Decision makers may leverage the capability of these companies for self-generation. Any spare capacity may be purchased by small power projects and used as back up. As the power generation in the country improves, companies may rely on small connections to the emerging grid as a way to abandon self-generation gradually.

The presence of industrial loads is a good opportunity for the government to create public-private cooperation. The cost of self generation is high (Foster and Steinbuks 2009). Decision makers can help these industries coordinate with local populations to create generating alternatives that would enhance the livelihoods of populations and lower the cost of the industry's power supply.

3.5 Conclusions

This paper responds to the gap in literature on the rural residential demand in Liberia. It shows that Liberia's renewable energy potential is large enough to satisfy the rural residential demand. Results also show that renewable fuels in Liberia provide lower LCOE than diesel but require a higher capital investment. Hydropower and biomass can provide electricity at acceptable prices for the rural population. Biomass technologies in particular offer significant benefits in the Liberian context. Diesel and solar PV on the other hand result in prices above the ability to pay of Liberians.

It is shown that DG is a promising parallel and complementary tool to the centralized energy policies in place. Both rural electrification and urban service through the expansion of the grid should be approached in complementary ways. The drafting of REMP by the RREA in Liberia provides an opportunity to identify areas in which DG and GE can interface.

It should also be considered that although decentralized rural renewable energy approaches have been proven feasible in other countries, such as Fiji, Nepal, Brazil, and India, implementation programs have not achieved the levels desired. Institutional barriers, high upfront costs, lack of credit, and high cost of appliances are seen as main issues (Shrestha 2005; Gaunt 2003; Nepal 2012; Martinot and colleagues 2002). These lessons can be used to inform the REMP and to empower the RREA for a better implementation strategy.

Electrification can play a role in job creation, well-being, urban-rural migration, environmental stewardship, education, and gender issues. Therefore it is recommended that rural electrification programs be included as a part of a wider development agenda (Andrade and colleagues 2011). The upcoming development of a second Poverty Reduction

Strategy (PRS2) in Liberia can integrate DG and rural renewable technologies as tools towards a sustainable future and development, especially when electricity's key role as a development catalyst is considered.

In particular, the use of biomass for electricity generation can be a key economic incentive for agriculture. Policies can be focused towards increasing income for small and medium farmers through the appropriate use of their food and cash crop waste. However, the use of biomass technology should not interfere with farmers' practices of crop waste management for soil nutrient replenishment. It is important to provide policies that balance both needs.

Education and technical training are key areas where electrification can serve as a catalyst. Provision of electricity needs to be accompanied by educational programs and entrepreneurial training that allow the customers to make better use of electricity (Martinot and colleagues 2002). Technologies highlighted in this paper can be used as "seeds" for educational efforts, human capacity building, and business creation.

In the end, economic and technical metrics should leave room for a more complex analysis process. Cultural, social, and economic preferences of Liberians should be considered. Andrade et al propose communities should be given autonomy, information, and ownership in the development of the electrification programs (Andrade and colleagues 2011).

A significant consideration not addressed in this paper is energy efficiency. The rural residential sector in Liberia can provide opportunities to implement efficiency measures from the onset, which are likely to be more effective. Use of thermal energy for cooking and water heating, for example, is an opportunity for efficiency improvement policies. As the electrification process continues, efficiency can play a significant role in cost reduction and environmental considerations in solutions for the provision of coupled thermal and electric energy.

Financing of a large electrification effort represents a challenge for policy, research, and development. Private–Public partnerships, civil societies, NGO's, and other organizations can be encouraged to enter the electrification market through financing mechanisms that take advantage of carbon markets and development funds. All stakeholders can be encouraged to collaborate to produce innovative financing and implementation programs.

In summary, the GOL and developing organizations can look at the renewable energy potential of Liberia as a way to help the country leap-frog technologies, encourage the protection of their environment, help economic recovery through high quality jobs, lead to a sustainable development economy, open up economic opportunities in the carbon market, and diminish social divides. These factors can help leverage aid dollars to better serve the development of Liberia.

3.6 Acknowledgements for Chapter 3

This work was funded by the National Science Foundation through the Graduate Student Fellowship Program. The authors thank Liberian stakeholders who generously provided meetings, information, and insight: Liberian Electricity Company, Manitoba Hydro, Liberian Environmental Protection Agency, Ministry of Land Mines and Energy, Ministry of Public Works, Rural Renewable Energy Agency, Buchanan Renewables, Research Triangle Institute, and Winrock International. We also thank the anonymous reviewers who helped us make this paper a stronger contribution.

3.7 Supporting Information

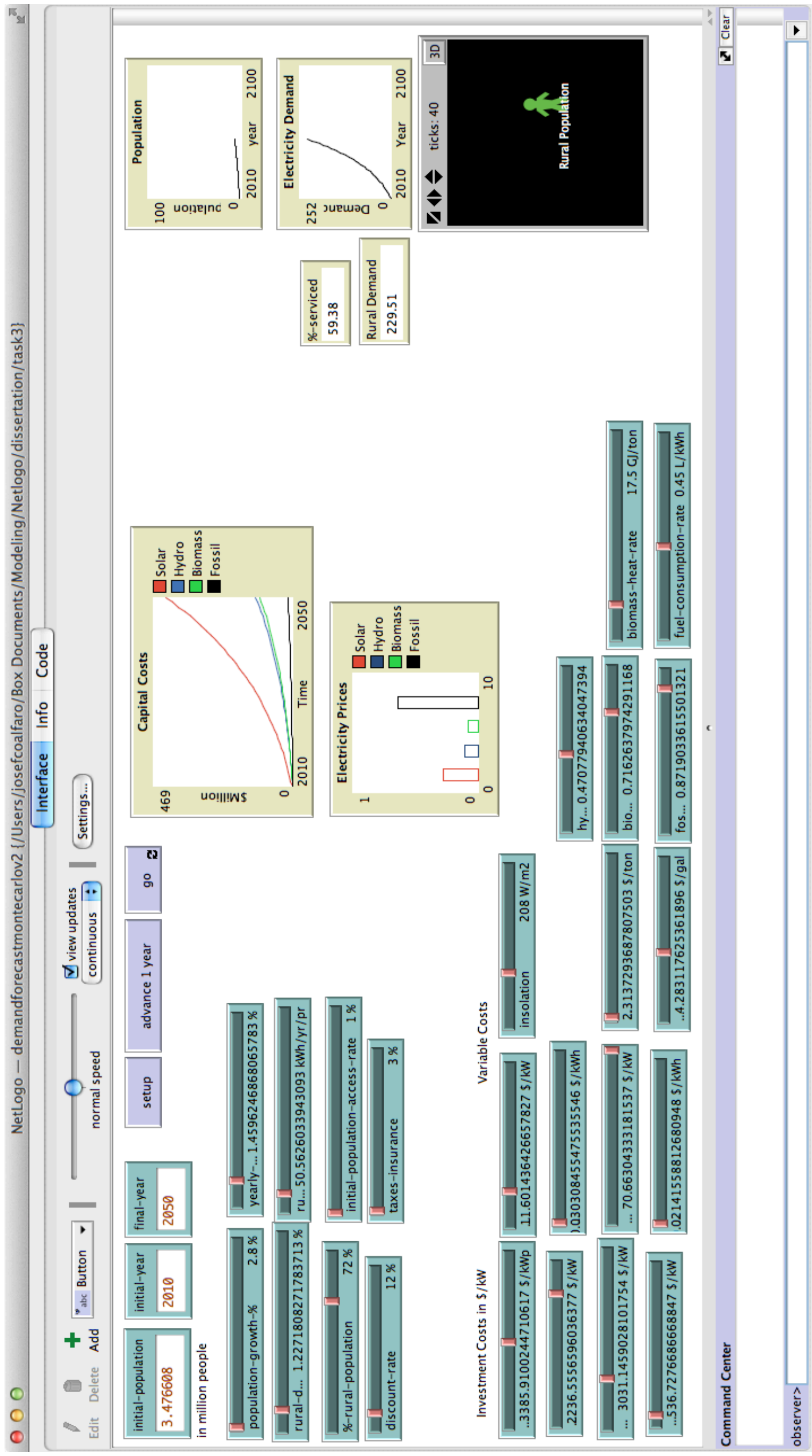


Figure 3-4: Modeling software screenshot

3.7.1 Sensitivity Analysis Graphs

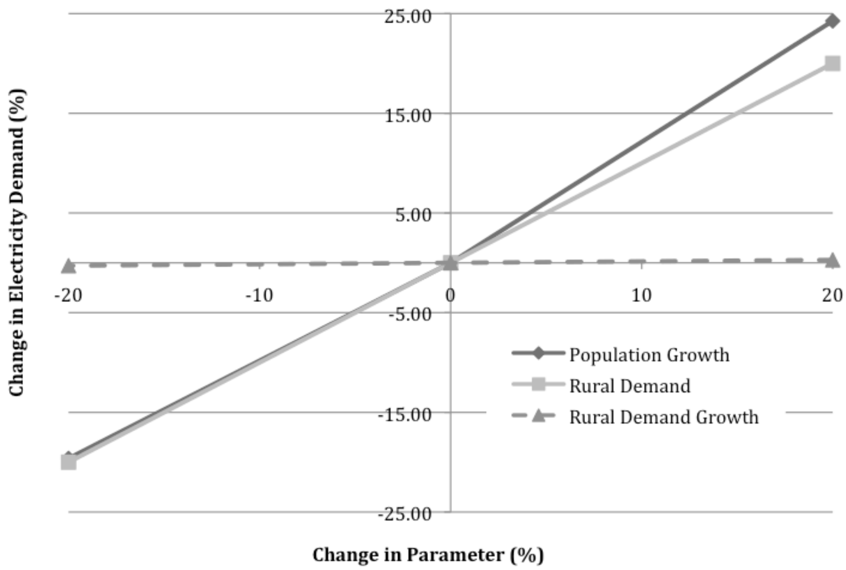


Figure 3-5: Sensitivity analysis for total electricity demand

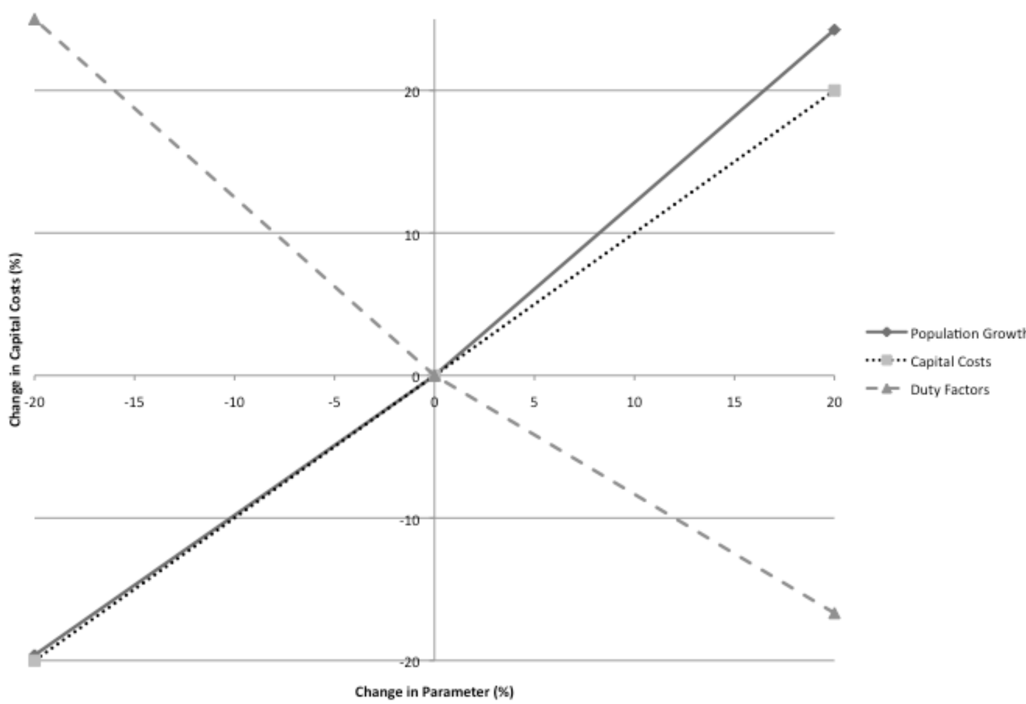


Figure 3-6: Sensitivity analysis for overnight capital costs

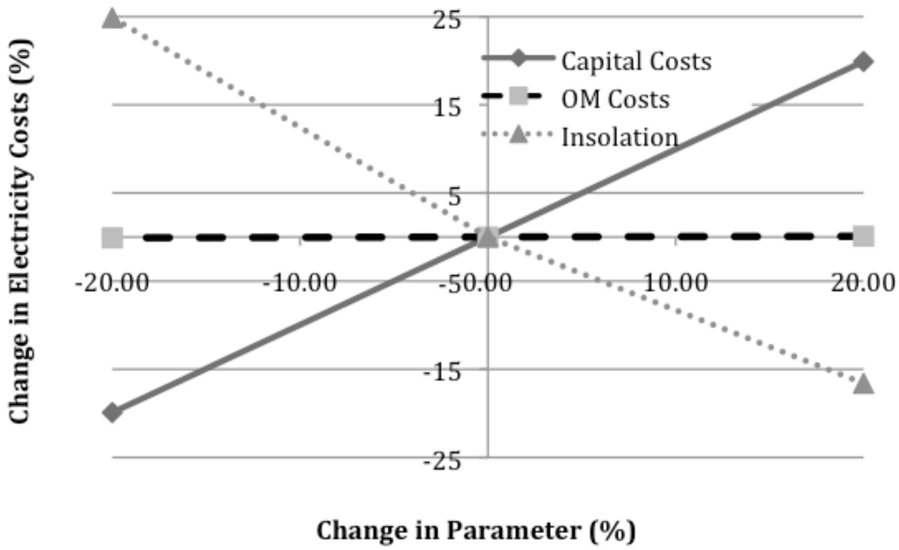


Figure 3-7: Sensitivity analysis for solar electricity prices

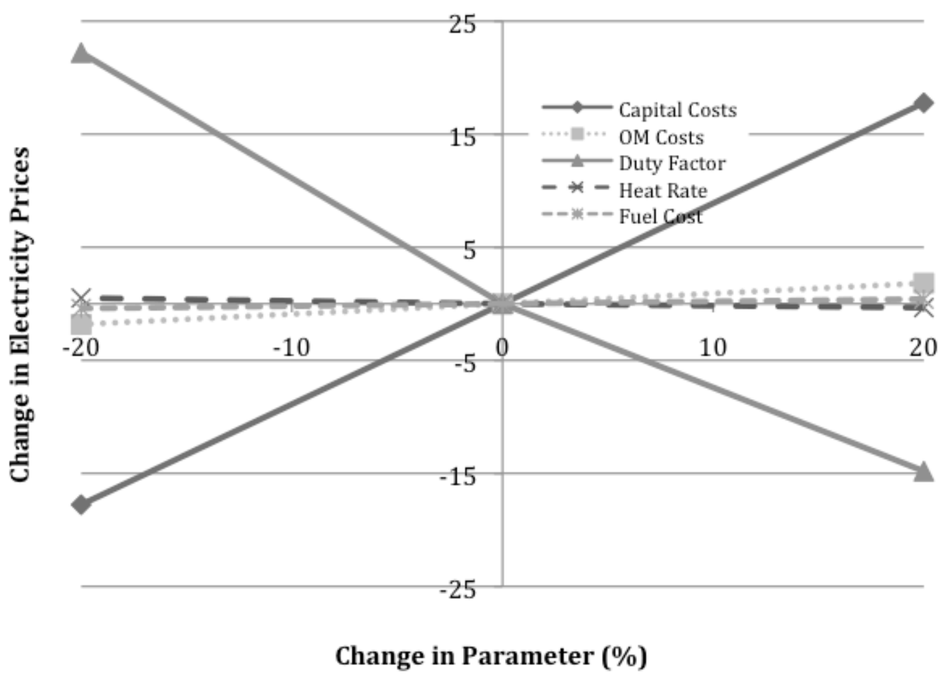


Figure 3-8: Sensitivity analysis for biomass electricity costs

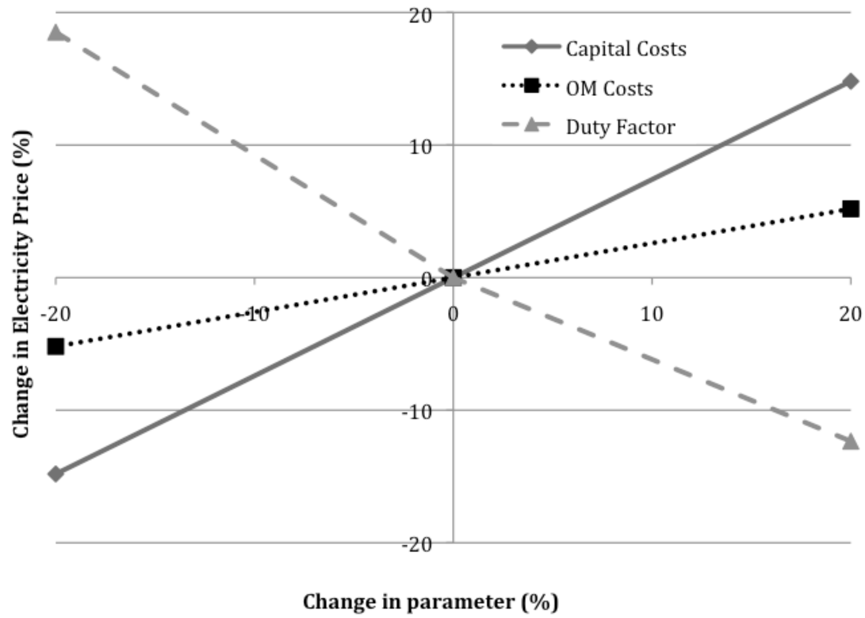


Figure 3-9: Sensitivity analysis for hydro electricity prices

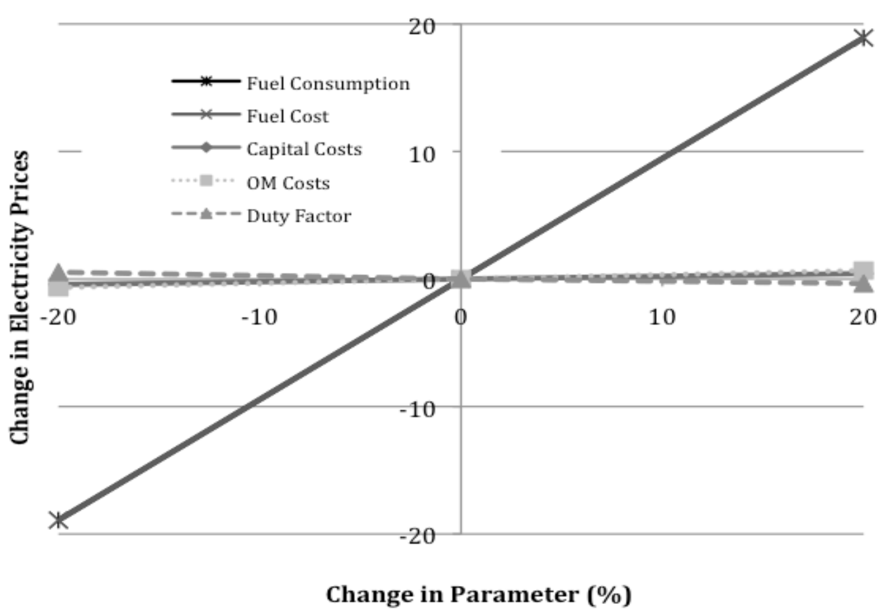


Figure 3-10: Sensitivity analysis for diesel electricity prices

Chapter 4

Informing the Development of the Renewable Energy Sector in Liberia through Industrial Ecology and Complexity

4.1 Abstract

The deployment of renewable energy is considered a necessary step towards sustainability and appropriate mitigation of greenhouse gas emissions. To be effective it must achieve a balance between a diversity of energy sources, locations for deployment and demand points, and transmission and local production. Less industrialized countries have the opportunity to leapfrog fossil based centralized networks for electrification by using appropriate technologies for production and delivery of renewable based electricity. This involves the emergence of a new system with interconnected technical, social, economic, and environmental layers.

The use of Complexity Science expands Industrial Ecology's capability to study these systems by providing tools that take in consideration those interconnections and can capture dynamic emergence, social value judgments, competing or complementary objectives, and imperfect economic incentives, while creating descriptive simulations of emerging phenomena. Through complexity, Industrial Ecology can be involved in the planning of a system at early stages in a dynamic, bottom-up approach that includes technical, environmental, and social considerations, and the context in which technologies will evolve.

This paper presents an Agent-Based Model that allows stakeholders to plan the development of electricity supply systems based on renewable energy. The model serves as a robust tool for policy experiments and scenario creation giving decision-makers illustrations of value judgment, path-dependence, and tradeoffs that occur during multi-

objective planning. The model is illustrated through the case study of Liberia, West Africa, arguably the least electrified country in the world.

4.2 Introduction

This paper provides an example of how Complex Systems (CS) or Complexity Science can be used to complement Industrial Ecology (IE). It attempts to extend the boundaries of IE by providing tools that can consider the dynamic and evolving nature of systems, and their dependence on the human and environmental context. The paper particularly considers the complexity of planning the emergence of a system under multiple objectives while taking into account associated tradeoffs in different metrics, which can include subjective concepts such as equality and social justice.

The vehicle for this contribution is a tool for policy planning experiments and scenario exploration in the development of renewable energy based electricity systems for less industrialized countries. The example of Liberia, West Africa is presented. The results show how a bottom-up, model of the interconnected environmental, social, economic, and technical layers can be useful during planning stages.

In this section the paper provides an overview of the complements that CS provides for IE and introduces the Liberian case study.

4.2.1 Complementing Industrial Ecology Through Agent Based Models

IE seeks to understand how industry interacts with its environment and uses ecology as a model for directing the growth or adaptation of systems in a pattern that emulates nature (Erkman 1997). Many of its tools, such as life cycle analysis (LCA), material flow analysis (MFA), and environmentally extended input-output assessment (EIO), study large systems from a top-down approach, using aggregate modeling.

Aggregate models are not ideal when informing policy due to their static and retrospective nature (Axtell and colleagues 2002). In general the IE tools fail to capture the dynamics and path dependence of systems (Ehrenfeld 2009). IE's basis on the ecosystem metaphor tends to lack consideration of the human and social context in which systems are developing, which are critical to sustainability (Ehrenfeld 2007). When studying emergent systems IE tools have to be complemented to understand the system's evolution and possible interventions toward sustainability.

From the first issue of the Journal of Industrial Ecology, researchers advocated the need for the field to remain knowledgeable of other modeling techniques for the system-based analysis of environment and industry to succeed (Ausubel 1997). The field of CS provides a complement to IE through the approach and tools it has fostered. CS moves away from reductionism and tries to capture unexpected macro-scale behavior resulting from micro-level interactions, also referred to as emergence. CS is said to be a natural and necessary foundation when dealing with heterogeneous interacting systems (DeLaurentis and Ayyalasomayajula 2009), such as those studied by IE.

It has been suggested that CS can significantly push the frontiers of IE, especially by increasing IE's interdisciplinary foundation and moving beyond understanding systems towards shaping them (Dijkema and Basson 2009). This work takes particular advantage of the CS tool of Agent-Based Models (ABM) to complement IE and provide a useful tool in shaping the electrification process in developing countries with renewable energy.

ABM focuses on a bottom-up approach to capture emergent behavior by conceptualizing the components of a system and their interactions instead of producing macro-level mathematical conceptualization. ABM's main application to IE has been identified as providing a low cost test bed for policy and planning scenarios (Axtell and colleagues 2002).

ABM also allows the study of emergent behavior through the mimicking of stakeholder inputs (DeLaurentis and Ayyalasomayajula 2009) allowing practitioners to include the social context in which systems are evolving. In other energy related studies it has been proposed that understanding participating agents' decisions determines the ability to create a sustainable energy sector (Kempener and colleagues 2009). This decisions may not be economic in nature and including them is important to the improvement of previously used policy models (Axtell and colleagues 2002).

4.2.2 Modeling Environmentally Dependent Socio-technical Systems

Socio-technical systems (STS) in which humans interact heavily with technical components have been gaining traction as an application of complexity to the IE field. Acknowledging the connections between social elements and technical and physical components that interact with each other is core to STS (Dijkema and Basson 2009). Recognition of these interactions allows IE to guide systems towards a flourishing future (Ehrenfeld 2007).

ABM is useful for simulations of complex adaptive STS (Nikolic and Kasmire 2013b). Through STS modeling, stakeholders can recognize the way their decisions and strategies can be used to craft policy that guides systems toward coupled human, environmental, and technical performance. Tradeoffs between different objectives can be analyzed without trying to predict the future but understanding the space of possible outcomes.

This paper extends the application of STS in IE with an example of environmentally dependent STS. These systems rely on the environmental resources as inputs for products and services and can't be decoupled from their natural context. Some examples are the mining, forestry, agriculture, and renewable energy industries.

Renewable energy is a promising alternative to fossil based electricity production. However, it is geographically constrained, has different technology costs, and its availability limits the size of production units that can be deployed. The result is the need to consider the location and size of available resources and demand points, and the appropriate network structure to connect them. All of this viewed through the lens of stakeholders' value judgments with regards to different generation technologies, deployment priorities, users' ability to pay, available financing for development, and complementary (or competing) objectives like increasing economic flows within communities, creating jobs, and enhancing social equality. An IE based approach would allow the identification of an appropriately diverse mix of fuels that enhances the economic performance of the system, increases social equality, and reduces environmental impacts.

The tool presented here uses ABM for the creation of master plans for renewable energy STS. The paper defines a renewable energy master plan as the desired fuel portfolio, general location of the resources to be deployed, network structure of the distribution system, and expected cost of electricity.

4.2.3 Policy Planning Experiments

Electricity is a key catalyst for social development and well being (Kooijman-van Dijk 2012a). It impacts all of the Millennium Development Goals established by the UN for poverty reduction, yet more than 1.4 billion people around the world still lack access to electricity (International Energy Agency 2010). Using traditional methods of electrification followed by developed countries is not a feasible option (International Energy Agency 2010). These methods involved a large dependence on fossil fuels and centralized infrastructure which have resulted in environmental pressures, class divides, increased debt, and fuel insecurities (Hiremath and colleagues 2007).

Less industrialized countries and rural areas are of particular importance because they hold the largest need for electrification increases (International Energy Agency 2010). Environmentally, these same communities are often endowed with a large renewable energy potential. In Sub-Saharan Africa, the area with largest electrification needs, the median renewable potential is 10-12 times the required demand (Deichmann and colleagues 2011).

Deploying renewable energy involves guiding and shaping the emergence of a new system. This means taking actions that can influence the macro-scale results through interventions at the system component level. It will call for careful policy considerations that include the unique challenges of renewable energy and non-economic factors such as resource preferences, job creation, social equality, and environmental concerns.

It is impossible for any tool to predict the exact way a process will develop. ABM should not be used as a predictive tool but as a scenario generation package (Kraines and Wallace 2006). However, modeling and simulations allow for the analysis of the space of possibilities that can emerge under specific stakeholder inputs. Policies and stakeholder preferences can be easily introduced into ABM as exogenous rules for the agents. Stakeholders can use simulations to understand how their decisions are portrayed, the differences between real and modeled decisions, and the macro-level characteristics imparted on the system as a result of those decisions. The simulations allow "*in-silico*" experiments impossible to conduct on the real system.

4.2.4 Liberia Case Study

To illustrate the capabilities of the model the case study of Liberia, West Africa is presented. As of the census of 2008, Liberia has a population of 3.47 million people, over 70% of them in rural areas (Republic of Liberia 2009). The country has an area of 111,370 km^2 and holds the largest remaining fraction of the Upper Guinean Tropical Rain Forest, a key biodiversity hotspot (Hamdan 2010; Conservation International 2007).

All services and physical infrastructure in Liberia were severely damaged during a 14-year civil war that ended in 2003 (United Nations and Republic of Liberia 2012). The International Energy Agency recognizes sub-Saharan Africa as the toughest challenge for electrification (International Energy Agency 2010) and Liberia's situation is one of the worst in the region. Less than 1% of the population has access to electricity, which comes with the highest cost in the region, 0.43 $/kWh (Africa Energy Unit 2011).

The Liberian Electricity Company has established a basic grid serving the capital city of Monrovia (Africa Energy Unit 2011). An emergency assistance program by international donors provided a base generation of high-speed diesel with a capacity of 9.6 MW (World Bank 2010). The grid serviced around 2500 customers in early 2010, mostly commercial and government buildings (Africa Energy Unit 2011).

New projects and policies are being pursued that intend to expand the country's electrification and coverage of the grid through increase in high-speed diesel, refurbishing of a heavy-fuel-oil facility, reconstruction of a hydro-electric facility, and connection to the Western Africa Power Pool (WAPP) (Africa Energy Unit 2011). These expansion plans will leave more than 50% of the rural population in Liberia with no access to electricity by the year 2040. The proposed grid will continue to depend largely on fossil fuels, a centralized structure and the WAPP, whose future performance is in question (Pineau 2008).

The government of Liberia has issued policies that support electrification efforts outside of the centralized scheme. The National Energy Policy issued in 2009 proposes the goal of universal access to modern energy services in the country (Ministry of Lands Mines and Energy 2009). The Rural Renewable Energy Agency (RREA) was established in 2010 (Africa Energy Unit 2011) with a mandate to utilize renewable energy projects to service the rural population.

RREA is in the process of establishing a rural electrification master plan. The model and framework presented here could serve as an important tool for the rural master plan and energy sustainability and independence. It could also serve as a building block for more detailed efforts in Liberia's different regions.

An analysis of the Liberian renewable energy potentials shows that the country has sufficient resources to fulfill the suppressed residential demand of the rural areas (Alfaro and Miller 2014). The projects suggested based on solar, mini-hydro, and biomass, result in levelized costs of electricity within the willingness and ability to pay of rural Liberians. However, an appropriate mix of fuels and delivery infrastructure was not studied.

Stakeholder Consultations

Significant consultations were conducted with Liberian energy sector stakeholders to develop this model. These consultations included government organizations, non-governmental organizations (NGO), and private sector companies. Table 4-1 shows a list of these stakeholders. Because of data gathered through consultations and the available grid expansion plans, the capital city of Monrovia is not included in the case study below.

Table 4-1: Stakeholders included in consultations

Governmental Organizations	Non-Government Organizations	Private Sector Organizations
• Ministry of Land, Mines, And Energy • Liberian Electricity Company • Ministry of Public Works • Liberian Environmental Protection Agency • Rural Renewable Energy Agency • Liberian Institute for Statistics and Geographical Information Services	• United Nations Environmental Program in Liberia • Center for Sustainable Energy Technologies • Winrock International, Liberian Party (Working on a USAID project)	• Buchanan Renewables • Manitoba Hydro, Liberian Party

4.3 Methods

The tool presented here is created in Netlogo, a free software for development of ABM (Wilensky 1999). The software is easy to install and provides user-friendly graphical components for the creation of "what-if" scenarios. The models can include geographic information systems (GIS) layers allowing the use of empirical data and the consideration of the highly geographical nature of renewable resources and load centers. These considerations create opportunities for stakeholders to use the tool with local data and without expensive licenses. It also incorporates the environmental and geographical context. An intuitive graphic user interphase (GUI) allows stakeholders to explore their relationship with the STS.

A general ABM created for the study of emergence of networks in unelectrified areas was used as basis for this model. A complete description of the general model can be found in the work of Alfaro, Miller, and Johnson (2014). The general model presents evolution of renewable energy networks in a clean-slate scenario with no existing infrastructure and no use of fossil fuels. The network evolves under stakeholder preferences for renewable energy deployment locations and connection priorities (Alfaro and colleagues 2014).

The model expansion makes it applicable to the development of master plans and includes value judgments occurring during multi-objective decisions. The model is integrated to GIS layers including the location and quality of renewable resources, allowing it to identify fuel portfolios, and the location and size of demand centers in Liberia. The model is modified to include the costs that correspond to the different technologies available in rural Liberia, Solar PV, Biomass direct combustion, and run of the river hydro. Wind is ignored due to its low potential away from costal areas (National Renewable Energy Lab; Africa Energy Unit 2011).

The expanded model seeks to minimize the levelized cost of electricity (LCOE). LCOE calculations include the cost of capital for generation and transmission equipment discounted over the life of the project per kWh of production, the cost of operation and maintenance per kWh, and the cost of fuels if any to produce a kWh of electricity. Detailed equations for LCOE and other metrics can be found in the supporting information.

Finally, the model captures competing or complementary objectives that can be present when electrifying a region through the formulation of four strategies. The strategies considered are: 1) using renewable energy to generate jobs, 2) using renewable energy projects to stimulate the economy, 3) increasing social justice through equitable investments in renewable energy in different regions of the country and 4) prioritizing the largest populations in the country to take advantage of possible economies of scale.

The decision strategies are balanced with cost minimization. In this way the model portrays the effects on the final system of the strategies used and the stakeholders ability to affect the emergence of different macro-scale system characteristics.

4.3.1 Model Components

The ABM contains 5 different agents: Environment Agents, Population Agents, Production Unit Agents, Line Agents, and the Observer Agent. For clarity model components are capitalized to distinguish them from real world counterparts.

Environment Agents

Environment Agents make up the World in which the simulations take place. They contain energy resources and geographic location data. Environment Agents are created through the use of GIS layers provided by the Liberian Institute of Statistics and Geographical Information Systems (LISGIS) that include the political boundaries of Liberia. Environment Agents also have access to hydrological, biomass, and solar data layers included in the World. An illustration of this concept can be seen in Figure 4-1 below.

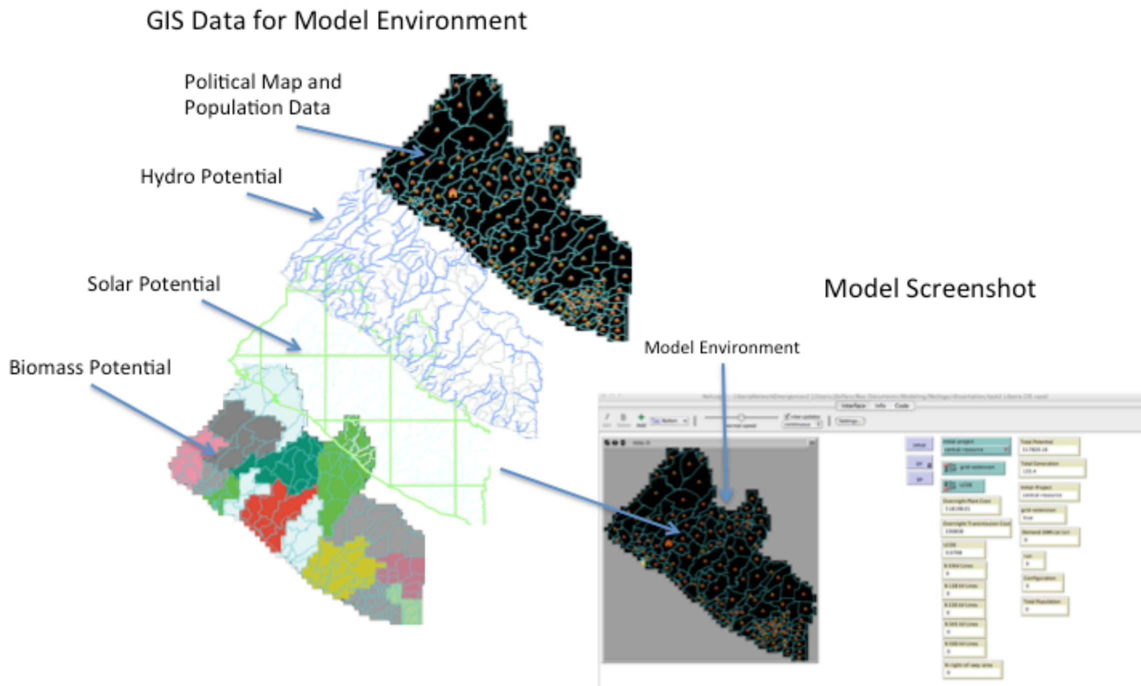


Figure 4-1: Models GIS and Data Layering

With the Netlogo GIS extension, typical GIS files such as shape, line, raster, and point data can be used. The data is matched to the size of the Netlogo World. In this model the World is a square of 51 x 51 Environment Agents. Each Agent has a side of 9.8 pixels. The software matches GIS layer boundaries to the maximum and minimum Environment Agents in the World and determines the approximate area that each one covers. This corresponds to 89.45 km^2 with sides of 9.46 km.

LISGIS created shape files that contain the political subdivisions of Liberia, including, in descending order, counties, districts, clans, and tribes. Each Environment Agent receives its corresponding data of county and district. The lower subdivisions are omitted because inhabitant data is not disaggregated to those levels in the Liberian Census (Republic of Liberia 2009).

All Environments receive the same insolation amount of 208.5 W/m^2. It is assumed that only 0.01% of each Agent's area is available for solar PV projects resulting in 8945 m^2 per Agent.

A report by the National Renewable Energy Laboratory is used to determine the biomass potential data in each Agent (Milbrandt 2009). Only the present potential from food and cash crop residues and waste in direct combustion applications is considered. County level potential can be seen in Table 4-2. The Model determines the number of Environment Agents that make up each county and the corresponding biomass potential per Agent. Each Environment Agent receives the corresponding biomass potential for the average of the county it belongs to.

Table 4-2: Biomass Potential per County*

County	Bio Power from Food Crops residue (GWh/yr)	Bio Power from Cash Crops residue (GWh/yr)	Total potential (GWh/yr)
Bomi	1.4	25.1	26.5
Bong	32.6	105.5	138.1
Grand Bassa	8.2	66.2	74.4
Grand Cape Mount	1.6	32.5	34.1
Grand Gedeh	6.4	9.8	13.2
Grand Kru	1.6	5.5	7.1
Lofa	18.9	46.9	65.8
Margibi	8.8	114.7	123.5
Maryland	8.8	32.2	41
Montserrado	35.8	184.9	220.7
Nimba	45.6	213.3	258.9
River Cess	2.1	8.5	10.6
Sinoe	5.1	32.1	37.2
River Gee	3.9	12	15.9
Gbarpolu	7.4	40.5	47.9
Total	**188.2**	**929.7**	**1,117.9**

*Source:(Milbrandt 2009)

Biomass can be moved limited distances if necessary to increase generation unit capacity. Costs for electricity production are affected when transporting fuels more than 32 km and distances beyond 160 km make fuel transportation costs prohibitive (Wiltsee 2000). Each Environment has access to the biomass potential of its Neighbors at a maximum distance of 33.45 km ensuring that transportation costs are negligible. Neighbors whose resources are used by an Environment loose the opportunity to deploy those resources themselves effectively reducing their biomass potential to zero. A schematic of this concept can be seen in Figure 4-2.

Hydrological potential data in the model is created from a map of suitable sites for small hydro generation published by the African Energy Unit (2011). Only 24 sites identified as small to medium potential (<50 MW) are included in this study because of the focus on rural areas and small projects. A few larger sites exist in Liberia not included here due to their consideration in the Monrovia grid expansion or their requirement for dams, larger civil infrastructure, and bilateral agreements with neighboring countries, which changes the scope of the technologies considered.

The Environment Agents that correspond to the location of the identified hydrological sites receive the hydrological potential of the project. Because the potential of each site is reported as a maximum potential the model uses a random number generator during each model run to assign actual potential following a uniform distribution between zero and the maximum. Figure 4-3 shows the small hydro locations.

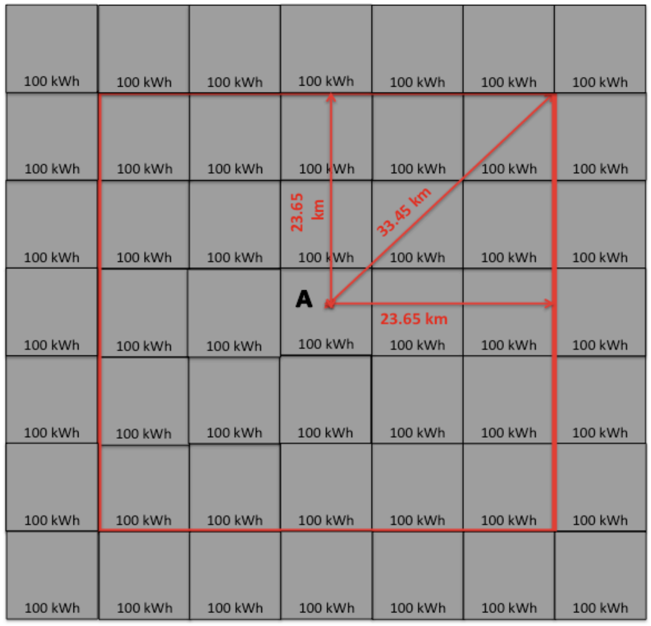


Figure 4-2: Biomass potential aggregation.
Environment A has access to biomass potential to a maximum distance of 33.45 km. That represents 24 neighboring patches. Including itself, in this figure Environment A has an aggregated potential of 2500 kWh/yr.

Population Agents

Population Agents represent the demand points in Liberia. They are created according to data obtained from LISGIS and the Liberian Census (Republic of Liberia 2009). Although LISGIS provided shape files that can represent the country down to the tribe distribution, the census data is only disaggregated to the district level. A Population Agent is created in the centroid of each shape representing the district. The Agents contain the information for the inhabitants of that district and their corresponding electricity demand. Demand is assumed at 250 kWh/pr/yr. This value is much higher than the present use for the Liberia grid, reported around 90 kWh/pr/yr (Africa Energy Unit 2011). However, it allows the consideration of increased demand upon electrification of new areas or the use of electricity for new productive uses. Figure 4-4 shows a schematic of the Population Agent construction in the model.

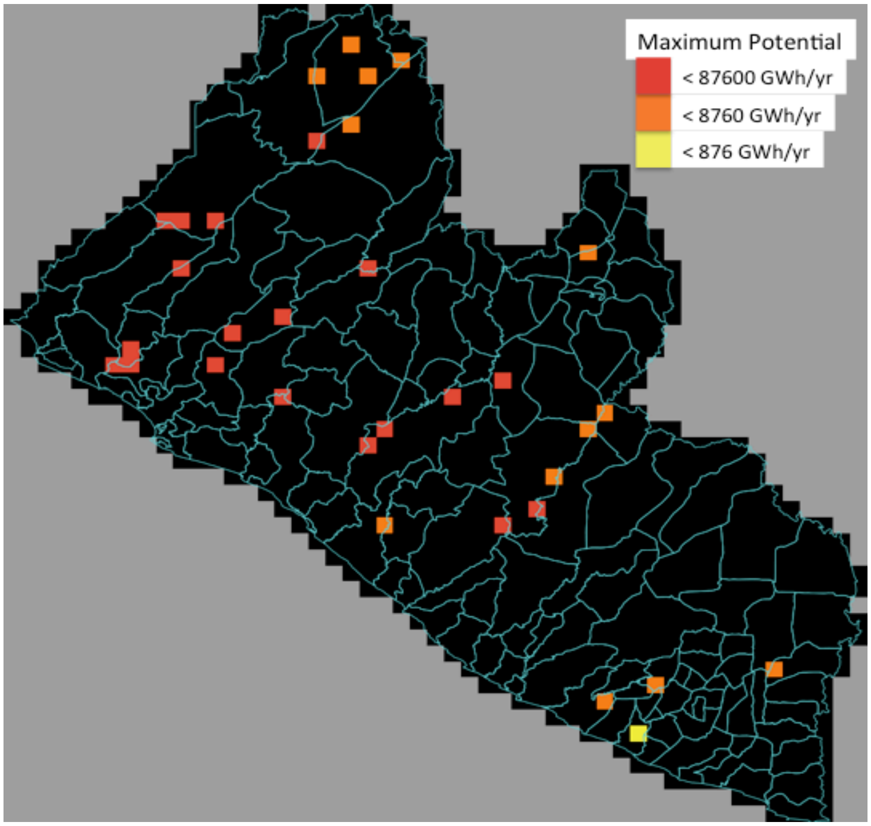


Figure 4-3: Location of potential small hydro projects and their maximum potential.

Throughout the model runs Population Agents can have three states, Electrified, Incomplete, and Unelectrified. Electrified Populations are those connected to a power source and whose electricity demand is being provided in full. Incomplete Populations are those connected to a power source but whose electricity supply is not complete. Finally, Unelectrified Populations are those not connected to any power source.

Production Unit Agents

Production Unit Agents are a representation of a power plant that uses the resources in a patch to create electricity. They inhabit an Environment Agent and use only one type of resource. Production Units use the resource in an Agent that results in the best option according to value judgments that will be discussed below.

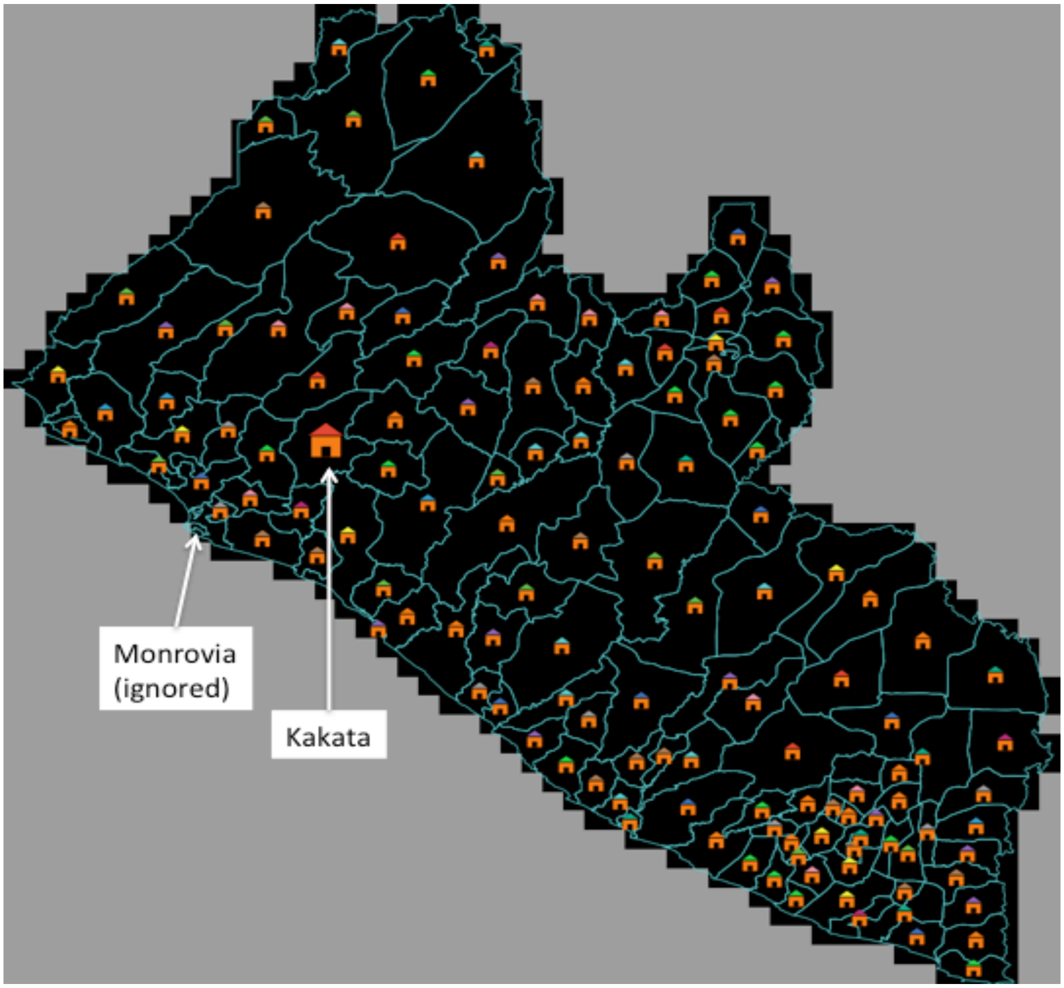


Figure 4-4: Population Agent construction schematic.
Each shape formed by the light blue lines is a GIS representation of the Liberian districts. In the centroid of each shape a Population Agent (houses) is created that represents the population in the district. Because this work focuses on rural populations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

The Production Unit will hold costs associated with generation of electricity and performance of the technology it is using in the Environment including operation and maintenance costs, fuel costs, duty factors, and efficiencies. Because these parameters have a wide range each model run a random number generator is used to provide the value for the Agents utilizing a triangular distribution between the minimum, average, and maximum values reported in the literature. These parameters can be seen in Table 4-3 below, which is adapted from Alfaro and Miller (Alfaro and Miller 2014).

Environment Agents can only host one Production Unit but a Production Unit and a Population can co-inhabit an Environment.

Line Agents

Line Agents represent transmission lines. They connect Production Units and Populations to each other carrying the electricity load. Transmission Lines can be of different grades and costs depending on load and distance. Line Agents characteristics can be seen in Table 4-4, which is adapted from Alfaro and colleagues (2014).

Observer Agent

The Observer Agent can be understood as an agent outside of the Environment, a central planner or decision maker. It is through this agent that the model can conceptualize different decision strategies or policy implementations. The Observer in this case follows four strategies that carry value judgments present in development efforts.

4.4 Agent Interaction and Decision Strategies

The model seeks universal electrification with the Observer creating Production Units at strategic locations that use the energy stores in those Environments. She connects them to Populations through Lines seeking cost minimization. The Observer follows the four strategies mentioned in earlier to choose the Environments for deployment. The result is that three competing or complementary objectives are being pursued in the model, universal electrification, cost minimization, and the Observer's development strategy.

Job Creation

In the job creation strategy the Observer seeks to use Production Units to increase the number of jobs available in the country. Each technology has an associated Job Creation rate in job-years per electricity delivered as seen in Table 4-5. The Observer picks the Environment that can provide the largest number of jobs created through the use of one of its resources. All resources in the Agents are considered but only one of the resources is developed. This means that an Environment with some solar and some biomass potential will be evaluated for the jobs created with each technology. The technology that creates the most jobs is the one chosen for deployment.

Each time step the Observer seeks to extend electrification at the minimum cost possible. He determines the Population that can be connected to the Production established at the minimum levelized cost of electricity and connects that population through the creation of a Line. Because the decision is being made based on levelized cost, which is normalized to the kWh of delivered electricity, small and large demand Populations can be compared to each other.

Table 4-3+: Parameter Values and Sources for Overnight Capital Cost Calculations

Parameter	Upper Limit	Average	Lower Limit	Sources
Small Hydro				
Hydro Capital Cost ($/kW)	2400	2000	1600	(Paish 2002; Africa Energy Unit 2011)
Hydro O&M ($/kWh)	0.04	0.025	0.01	(International Energy Agency 2011)
Hydro Duty Factor (%)	60	40	20	(International Energy Agency 2011)*
Small Biomass				
Biomass Capital Cost ($/kW)	4100	3350	2600	(International Energy Agency 2011)
Biomass O&M ($/kW)	77.34	64.45	51.6	(EPA 2010)*
Biomass Fuel Costs ($/ton)	3	2	1	(Schmall and Williams 2011) Source provided an average, authors create 50% limits around it
Biomass Duty Factor (%)	90	80	70	Assumed
Biomass Heat Rate		17.5		(Scurlock 2001; Milbrandt 2009), Assumed as stable.
Solar PV				
Solar Capital Costs ($/kWp)	4100	3400	2700	(International Energy Agency 2011)
Solar O&M ($/kW)	14.02	11.68	9.34	(International Energy Agency 2011)*

*Source provides average value; upper and lower limits are defined as +/- 20% of the average

+Adapted from (Alfaro and Miller 2014)

As the model progresses and the new grid expands the Observer finds situations where the existing Lines have to be upgraded to be carry the load demanded according to Table 4-4. In these cases the cost of upgrading the lines is included in the levelized cost of electricity. Equations for these calculations can be seen in the supplementary information.

The Observer expands the grid with the Production Unit established until no economically viable expansions exist. This could mean that the Unit is out of capacity or that the costs to expand the grid any further are not competitive with the costs of starting a new project. In these cases the Observer creates a new Unit at the next location that provides the largest amount of jobs.

This process continues until all Populations have been electrified.

Table 4-4+: Loadability Limits for Lines Used in the Model

		Distance Limits and Load Limits*					
Line Rating	Costs** ($/km)	< 80 km	80-100 km	100-200 km	200-300 km	300-400 km	> 400 km
33 kV	23,000	0-14.5 MW	0	0	0	0	0
138 kV	90,000	14.5 – 156 MW	<143 MW	<117 MW	<91 MW	<67.6 MW	<57.2
230 kV	192,000	156 – 435 MW	143-398.75 MW	17-326.25 MW	91-253.75 MW	67.6-188.5 MW	57.2-159.5 MW

*Loadability limits were determined using data in (Glover and colleagues 2012b)

**Cost data obtained from (Deichmann and colleagues 2011) for 33, 138, and 230 kV and extrapolated from there for 345 and 500 kV

+Adapted from (Alfaro and colleagues 2014)

Economic Stimulus

Literature has shown that renewable energy technologies create a significant economic flow within communities where they are located (Buchholz and Da Silva 2010). The different levels of economic flow can be seen in Table 4-5. In this strategy the Observer seeks to create the largest economic activity inside the communities. She creates a Production Unit on the Environment that provides the most economic inflows considering the resources available. As in the job creation strategy only one technology is developed in the Environment Agent chosen according to the capabilities of those technologies to create economic inflows.

As with the job creation strategy the Observer extends electrification from the Units seeking to minimize the levelized cost of electricity. New Units are created as capacity is exhausted or economically viable connections are no longer available.

Table 4-5: Job and Economic Inflow Generation for Each Technology

Technology	Jobs Created (Job-years/MWh)	Economic Inflows ($/MWh)
Solar	880	9.1
Biomass	210	36.8
Hydro	280	0

Equal Development

Liberia's history has seen a significant amount of clashes due to inequality between social classes and ethnic groups (Ellis 2001). In this strategy the Observer seeks to provide equality of development among the country's political subdivisions. Thirteen of the fifteen counties are considered, excluding Montserrado and Sinoe County. Montserrado is excluded because of its superior development when compared to the others. Also, it holds the capital city of Monrovia expected to be electrified through the centralized plans described earlier. Sinoe County holds Liberia's most important natural reserve, Zappo National Park. To avoid environmental degradation in this area the Observer excludes this county for location of Production Units.

To follow this strategy the Observer places a Unit beginning with Bong County. A Production Unit is created in the county's Environment Agent that can create the most jobs, similar to the job strategy described above. However, once expansion is exhausted for that Unit the Observer picks the next county following the order on Table 4-2 and places a Unit in the Environment of that county that can provide the most jobs repeating the process until all Populations have been electrified.

Largest Population

In the largest population strategy the Observer prioritizes load centers with the most inhabitants. To do this the Observer determines the Environment Agent that can provide the lowest levelized cost of electricity for the largest Population. In this model this is always the semi-urban town of Kakata. Equations for this calculation can be seen in the supporting information.

The Production Unit and grid established are expanded as before by connecting the Population with the lowest levelized cost of electricity each time step until grid expansion is no longer feasible. The Observer then finds the largest Population in terms of inhabitants remaining in the World and picks the location for a new Unit based on the levelized cost of electricity for that Population. This cycle continues until all Populations are electrified.

4.4.1 Model Simulations

To capture the technologies' variability in cost and possible performance, and the variability in the hydro potential availability, 50 model runs are performed for each strategy. The jobs, economic inflows, fuel portfolios, location portfolios, and resulting LCOE are compared for each strategy. This allows stakeholders to see the way their decision strategies and value judgment affect the resulting master plan.

With the results tradeoffs between affordability, economic stimulus, jobs created, equality, and fuels utilized can be clearly outlined. This allows the ABM to act as a robust tool for policy planning. It also allows the tool to expand the capacity of IE tools with the capture of the dynamic evolution of the renewable energy system in the context of the environmental resources and human actors and under different decisions beyond the economic. It successfully becomes a descriptive model and moves away from being a predictive tool.

4.5 Results and Discussion

In Figure 4-5 the results for levelized cost of electricity, economic inflows, jobs created and fuel portfolios for each strategy are summarized, illustrating the tradeoffs for the multiple objectives pursued. For levelized cost of electricity the most economic strategies are Job Creation and Largest Population. The most expensive strategy is the Equal Development Strategy followed by the Economic Stimulus strategy.

Not surprisingly the Economic Stimulus strategy results in the highest level of community inflows. The Job Creation strategy results in the lowest level of economic stimulus.

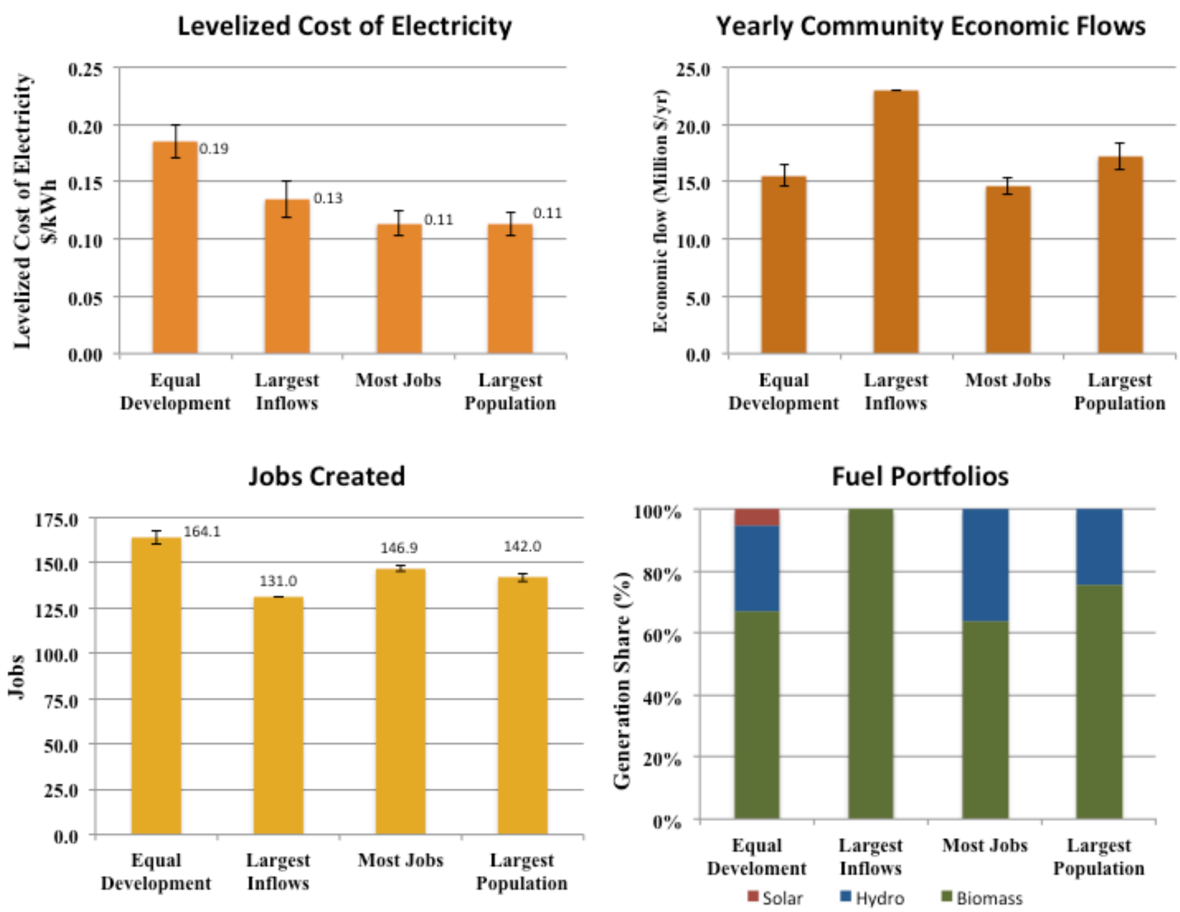


Figure 4-5: Summary of Simulation Results

Interestingly, the Equal Development strategy, and not the Job Creation strategy, results in the largest number of jobs. Although in the Job Creation strategy the Observer seeks to maximize jobs the Observer is also extending electrification through cost minimization. In Equal Development some of the cost minimization is sacrificed to create Units in different counties. This results in a higher number of Units created and associated higher job development as can be seen in Figure 4-6.

Biomass technology dominates the fuel portfolios of all the strategies from a lowest level of 64% in the Job Creation strategy to a full 100% in the Economic Stimulus strategy. Hydro represents the largest share of the remaining generation. Solar PV achieves very little penetration being used only in the Equal Development strategy at 5% of total generation.

High reliance on biomass should be carefully considered. Biomass produces economic inflows within communities and allows the best use of local resources (Buchholz and Da Silva 2010; Dasappa and colleagues 2011). It is a dispatchable technology, which provides flexibility for the use of energy when needed and avoids the intermittency related with other renewable energy technologies. Further, it can provide alternative uses for waste and byproducts from the agricultural sector. The symbiotic relationships created are interesting for development of Industrial Ecology complexes.

However, a high reliance on one fuel can create resilience issues. Any shock to the agricultural sector may induce a significant problem in the energy sector. In the case of the Economic Stimulus strategy no alternative fuel is available to absorb a shock.

Figure 4-6 shows the location portfolio of each strategy including the number of secondary grids in each county and the percentage of Production Units that each county receives. A secondary grid is a group of Populations and Production Units connected to each other by a series of Line Agents. Having just one connection to the grid would make a Population a part of that secondary grid. If two grids were connected to each other through one connection between any two points in their network they would no longer be considered two separate secondary grids but one. They are referred to as secondary because it is assumed that the primary grid in Liberia will be the larger central network planned to service the capital city and surroundings.

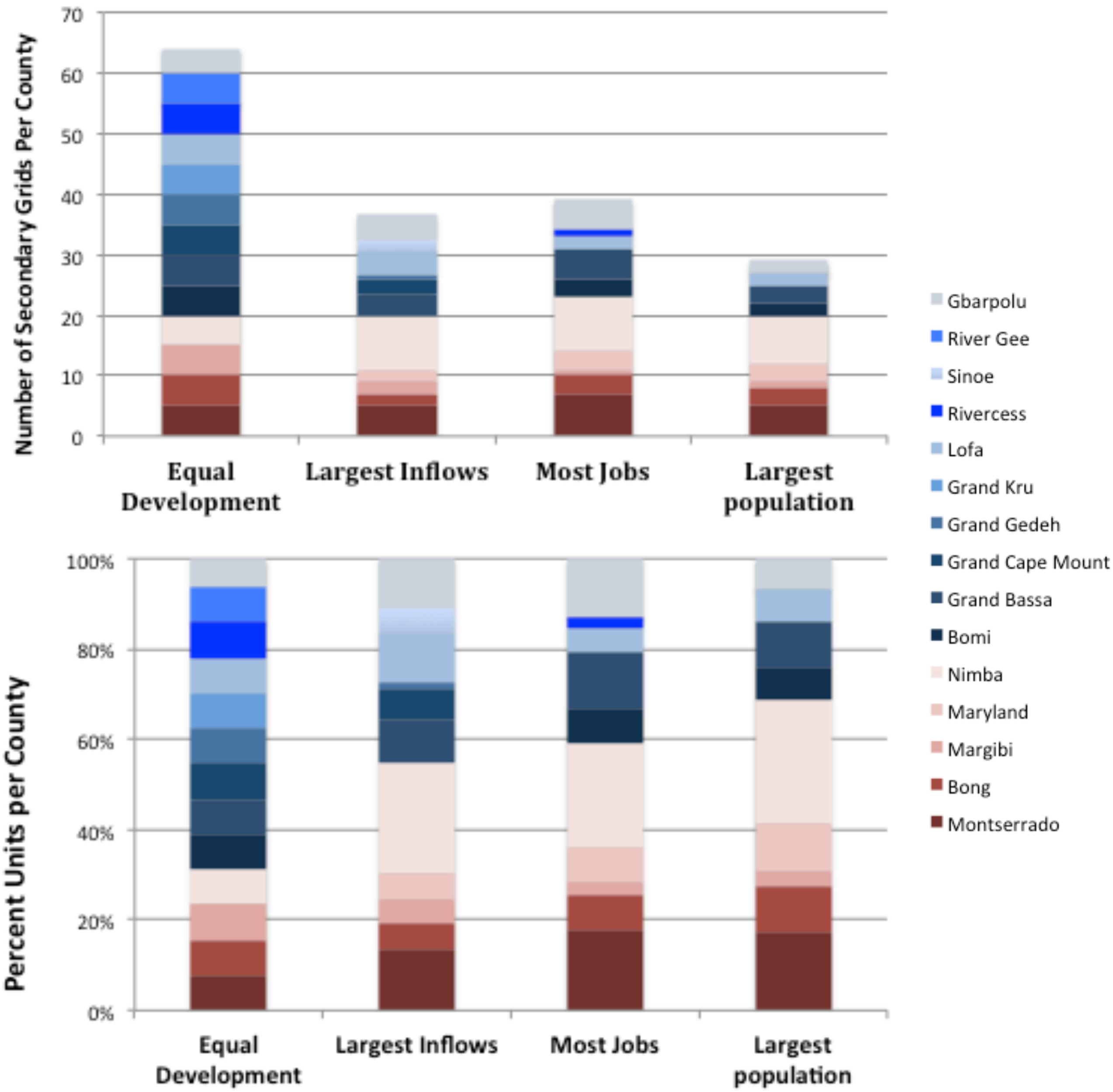


Figure 4-6: Location portfolio for development strategies.
The top chart shows the number of grids created in each county. The lower chart shows the percentage of Production Units in each county.

The number of secondary grids is important because it points to the level of management complexities that would be present in an electricity system. It also points to the possible stability of a system. With a high number of secondary grids the complexity of the system may increase. There are more separate clusters of electricity transmission that need to be considered, managed, and maintained. This may also reduce the ability of each cluster to respond to shocks. If more Production Units are interconnected to populations, a failure in one may be absorbed by increased production in a different unit. Even if the second Unit does not have sufficient capacity to absorb the total demand of a failed unit, the resulting disturbance in the secondary grid would be lower than if a complete shut down was experienced.

The figure shows in blue tones the counties that have historically been perceived as lagging in development. In red, the figure shows the counties that have been viewed as more developed or favored during the Liberian conflicts.

Figure 4-6 shows that the highest number of secondary grids occurs in the Equal Development strategy. This is important because although it creates higher complexity of management it also results in a higher number of jobs created. This is desirable in a country where only around 17% of the available workforce has paid employment (Zulu 2012).

The lowest number of secondary grids occurs in the Largest Population strategy. This reduces the management complexity and achieves the lowest cost of levelized electricity. The strategy is also competitive with the level of economic inflows it creates, second only to the Economic Stimulus strategy. However, most of the Production Units in this strategy are located in counties that are leading the way in development. These counties, already seen as favored, will likely capture the economic inflows and jobs generated causing concerns for stakeholders.

The highest percentage of Production Units located in less developed counties occurs with the Equal Development strategy. However, as mentioned earlier this results in the highest cost for electricity.

While the strategies presented here balance one complementary objective with cost minimization it is possible to create hybrid strategies that balance two or more objectives. Several different approaches are available for this but two main schemes seem promising.

The first is to provide weighing factors for decision-making that would rank the renewable resources available. These factors could be tuned to resemble stakeholder desires or input. For example a central planner may desire to pursue job creation, economic stimulus, and equality at once. The planner may determine that most importantly he desires job creation, while economic stimulus and equality are about equal but lesser than job creation. The Observer Agent can be programed to normalize all the possible values for each Environment by using the maximum available score. Then a weight factor of 50% can be given to job creation, and 25% each to economic stimulus and equal development. Each Environment would then receive a grade between 0 and 1 with the highest grade being the most desirable Environment. The following equation illustrates this process:

$$G = \frac{0.5 * Jobs\ Created}{Maximum\ Possible\ Job\ Creation} + \frac{0.25 * Economic\ Stimulus}{Maximum\ Possible\ Stimulus} + \frac{0.25 * Equality\ Value}{Maximum\ Possible\ Equality\ Value}$$

In this equation G is the grade for the environment and maximum possible values for job creation and economic stimulus would be equal to the maximum values available in the world. A value for equality would have to be developed, for example by providing each county a grade according to its Human Development Index (HDI). The equality value would then be the inverse of the HDI so that counties with lower development are preferred.

A second alternative is to engage stakeholders in an Analytical Hierarchical Process (AHP). In AHP a scientifically derived method is used to arrive at a linear expression that sets priorities in multi-objectives decisions (Mordeson and colleagues 2013). A matrix of comparisons is created that can be used to gauge the importance of each factor for the stakeholders. This differs from the weighing factor approach presented above in that it follows a structured process and not an objective value. This is particularly useful when the priorities compared are not easily evaluated against each other such as the ability to bring rural health improvements, the mitigation of climate change, and curtailment of migration. It is also powerful when multiple stakeholders must provide their evaluation and allows for the modeler to come to a consensus with the participants.

The resulting linear expression can be used to create comparisons of the Environments potentials according the stakeholders input to the AHP. This type of analysis has already been used in electricity planning efforts in countries like Pakistan and Jordan (Kablan 1997; Amer and Daim 2011). In the model presented here the linear expression resulting from the stakeholder consultations would form the decision strategy for choosing Environment for deployment that the Observer follows.

4.6 Conclusions

This paper provides an example of complexity tools used to complement IE and policy planning. A robust tool for the study of emergent renewable fuel based electricity grids was presented through the case study of Liberia, West Africa. It is shown that the tool is able to model the emergence of systems while capturing the context those systems evolve in and the interactions between human, natural, and technical layers, especially decisions from stakeholders and their associated value judgments.

The tool presented is an example of how IE can provide a policy planning approach towards the development of industrial sectors. It showcases the opportunities to do this at the onset of the planning stages for better impacts on the overall system sustainability. It is also an example of how IE can reduce limitations outlined in the literature that involve the ability to capture the dynamic emergence of systems, the system development context, human decision-making and value judgments, and different scales of analysis.

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

Model results can provide create funding justification for data gathering. For example, the biomass potential data in Liberia is critical to the findings and its expected share in all the scenarios justifies investment in refining and verifying the data. The same can be said for suppressed demand surveys of populations and disaggregation of Liberian census data to higher levels of resolution such as clans and tribes.

Figures 4-5 and 4-6 are an important asset for the planning process. However, further steps will be required before applying the results. Stakeholders should be involved in a validation and verification process. Once their feedback is incorporated consultations for tradeoff analysis can be conducted following appropriate methods.

While the results provide a wealth of information, the human actors in the real system will be responsible for following any strategies outlined here or modifying them. The authors hope to engage stakeholders in these sessions pursuing the literature recommendations for Industrial Ecology practitioners to not stop at system understanding but "make a leap towards system shaping – a transformation from valuable analysis to deeper understanding and, ultimately, to responsible action" (Dijkema and Basson 2009).

4.7 Supporting Information for Chapter 4

The following equations are used by the Population Agents and Observer to calculate the LCOE.

LCOE is calculated with equation 1.

$$LCOE_{j-i} = \frac{D_j * UCC_t * CRF_t}{DF_t * Q_{i-t} * 8760\frac{hrs}{yr}} + \frac{(d_{j-i} * TCC_{j-i} + C_{CU}) * CRF_{trans}}{Q_{i-t} * 8760\frac{hrs}{yr}} + \frac{O\&M_t}{8760\frac{hrs}{yr}} + \frac{PL * FC_t}{HR_t * \eta_t * 278\frac{kWh}{GJ}} \quad (1)$$

where:

$LCOE_{j-i}$*=levelized cost of electricity for population j from Environment Agent or cluster i in \$/kWh*

D_j*= average demand of population j in kWh/yr*

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

DF_t*= duty factor of technology t (for solar technologies the duty factor can be calculated using the conversion factor for insolation in Liberia)*

Q_{i-t} *= electricity potential in Environment Agent or cluster i for technology t in kWh/yr*

d_{j-i}*= distance from population j to Environment Agent or cluster i in km*

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

CRF_t*= capital recovery factor for technology t*

CRF_{trans}*= capital recovery factor for transmission infrastructure*

C_{CU}*= cost of cluster update if any*

$O\&M_t$*=operation and maintenance cost for technology t in \$/kW*

PL= price levelizing factor for fuels assumed

FC_t*=fuel cost for technology t in \$/ton*

HR_t*=heat rate of technology t in GJ/ton*

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 a project of technology t in years assumed as 15 for solar, 40 for transmission infrastructure, and 30 for all other technologies

t&i = taxes and insurance assumed at 3%

$CRF_{trans} = CRF_t$ *for n_t = 40*

and

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

and

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

where

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

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

Chapter 5

Conclusions

5.1 Summary

This work has provided new tools for planning of renewable energy deployment based on Complex Systems concepts of Agent Based Models (ABM) and emergence. ABM is offered as a flexible tool that can fill several needs identified in the literature. Gaps identified through the energy planning literature include the ability to consider renewable energy decentralized generation, rural electrification plans, poverty reduction objectives, and bottom-up simulation-based policy planning tools (Urban and colleagues 2007; Bhattacharyya and Timilsina 2010). The dissertation also fills gaps in the Industrial Ecology literature (IE), in particular through creation of models that are dynamic, capture emergence, provide descriptive and not prescriptive results, and allow the integration of the social, environmental, and technical spheres (Dijkema and Basson 2009; Ehrenfeld 2009, 2007).

ABM is able to create disaggregated conceptualizations that include the technical, economic, and social layers that interact in the development of the system. Stakeholders' strategies for deployment can be captured even when they do not follow econometric parameters for certain decisions. The tools created can portray path dependence and what-if scenarios for policy analysis. They can incorporate heterogeneous entities and their interactions, such as Environment Agents that provide renewable energy electricity and Production Units that use that electricity but both respond to different rules and interactions. Geographic Information Systems (GIS) are easily integrated to simplify data management and provide a realistic environment layer for the models.

Chapter 2 shows how ABM can be used for the planning of renewable energy grids in the absence of fossil fuel options and existing electricity infrastructure. This situation is particularly applicable to less industrialized countries (LIC). It shows how the stakeholders' preferences for renewable energy deployment and their desire for participatory decision making can change the economic performance of the resulting system. The model showcases how the independent variables of population demand, population size, and available renewable energy potential can be considered for appropriate strategy and decision formulation.

The concept of stress, the ratio of total demand to total electricity potential, is introduced to examine where the considered strategies can be more economical. In areas of low stress a bottom-up strategy that allows local participation and identification of renewable energy opportunities results in the most economic approach. In areas of high stress a centralized decision strategy that places emphasis on balancing resource size and distance to demand points (presented as the *Resource Centrality Index*) is most economical, at the expense of excluding local participation.

Electricity availability acts as a buffer for costs of development. The models show that as potential for renewable electricity increases the general costs of the delivery infrastructure decrease. The bottom-up strategy with participatory approach is benefitted by this phenomenon more than the other strategies. With higher electricity potential the bottom-up strategy remains more economic for a larger range of stress levels.

These results provide further support for the need of regional considerations of renewable electricity potentials. It informs policy by identifying scenarios where inclusive decision-making may not be possible due to economic and technical constraints. It also expands the definition of regions that are suitable for micro-grids or decentralized generation. Literature often identifies these regions as rural, isolated, with low demand, or sparsely populated (Parshall and colleagues 2009; Levin and Thomas 2012). However, Chapter 2 results suggest that if the electricity potential is high enough, none of those qualifiers are necessary for the use of renewable energy in electrification. A high potential reduces the cost of the delivery system and provides economic competitiveness even in situations with high population and high demand as long as the stress in the total system can be maintained low.

Chapter 3 shows how the Liberian situation of suppressed demand in rural areas can be estimated through a Monte Carlo analysis. It shows that the Liberian demand for the rural residential sector by year 2050 can be expected to be 235±75 GWh/yr to service 61±33% of the rural population. This covers comfortably the 50% of the rural population in Liberia expected to remain unelectrified through the centralized plans around the city of Monrovia.

The Chapter also shows that the country has sufficient renewable resources to supply that suppressed demand even if only one technology was to be developed at a time. Only technologies available in rural Liberia were considered, which ignores wind and projected forestry and energy crops. All technologies were evaluated as stand-alone micro level generation. This focuses the work on the technical feasibility to supply the demand with renewable energy only and avoiding fossil fuel backups. The costs of supplying demand through small diesel-fuel generators was presented for comparison and results in a cost of electricity above the Liberians ability to pay.

The expected costs of electricity from a fully decentralized system in Liberia are within the ability and willingness to pay of rural Liberians if hydro and biomass technologies are used. All three renewable technologies provide costs that are competitive with the present urban grid in Liberia at 33, 11, and 8 cents/kWh for solar, hydro, and biomass respectively. The costs from mini-hydro and small biomass are also competitive with the expected least cost future performance of the expanded grid connections in Liberia. These results suggest a significant opportunity for development of mini-grids in rural areas, especially those expected to remain disconnected form the central grid.

Chapter 3 provides significant opportunities to cover the residential demand of Liberians not expected to be a part of the centralized electrification. It shows that the calls for parallel efforts for rural areas' electrification (Africa Energy Unit 2011) can be answered economically. Further, it shows that Liberians are facing a high cost of self-generation through diesel, kerosene, batteries and other alternatives (Alfaro and Miller 2014). Significant savings for these populations can be provided through renewable electrification projects.

Chapter 4 is an expansion of the model in Chapter 2 to the case study of Liberia. The expansion is used for three main purposes:

1) to provide a more realistic scenario of interconnected renewable energy grids in Liberia and their expected costs,

2) to validate model use for policy scenario generation and experiments that do not rely on econometric parameters only.

3) to address the case of mixed supply of fuels for electrification of rural and remote areas which was not addressed in Chapter 3.

The model is presented as an application of complexity in Industrial Ecology. It advances the field of Industrial Ecology (IE) by allowing stakeholders to consider more broad parameters for decisions makers, presenting descriptive options for policy planning and not prescriptive optimums, and by allowing IE to consider a wider set of considerations in the modeling of socio-technical systems, their interactions with nature, and dynamic evolution of systems and their relationships.

The chapter shows how the ABM can consider multiple objectives that present a tradeoff analysis. The objectives are not necessarily econometric in nature but consider complementary or conflicting objectives such as creating jobs, stimulating rural agricultural economies, increasing social justice, and prioritizing large pockets of population. The results identify that trade offs between cost of electricity, jobs created, economic inflows, and equality can be capture and methodically analyzed. It is seen that focusing on larger populations and job creation result in the lowest cost of electricity. This is important for the affordability of the service. However, these strategies create lower economic flows within communities failing to capitalize on this aspect of renewable energy generation. The two strategies also result in a large number of investments placed in regions of Liberia already viewed as having advanced development relative to the rest of the country.

Social justice comes at a price since following the equal development strategy results in the highest cost of levelized electricity. This means that pursuing equality may result in lost opportunities for electricity uptake. However, this strategy generates the most jobs. This is an emergent characteristic that results from the number of production units that had to be created to fulfill the demand. The job creation strategy produced a high number of jobs but resulted in less production units taking advantage of economies of scale in transmission when compared to the equal development strategy.

It is interesting to compare the results in Chapters 3 and 4. Chapter 4's Economic Stimulus strategy relies fully on biomass. It differs from Chapter 3 deployment of biomass in that it includes transmission infrastructure and reduces the number of generation units required. This raises the LCOE from $0.08/kWh in the fully decentralized case of Chapter 3 to $0.13/kWh but reduces management complications. Although this is a significant increase in cost, the service would remain accessible to the rural Liberians ability to pay of $13 per month and willingness to pay of $10 per month (Winrock International 2011b, 2011a). Liberians would be able to afford 184 – 240 kWh/pr/yr. This consumption is more than double the present consumption in Monrovia (Africa Energy Unit 2011).

The inclusion of hydro technology in the Job Creation and Largest Population Strategies achieves a lower electricity cost. Technology costs and location of hydro resources buffers the cost increases created by the addition of the transmission infrastructure. Using both hydro and biomass achieves a cost of $0.11/kWh, which is comparable to the deployment of hydro alone presented in Chapter 3. These two strategies also remain accessible to the rural Liberians ability and willingness to pay. With this strategy their consumption could increase to 218 - 283 kWh/pr/yr.

It would be important for future work and further policy planning to consider the possible increases in income of the rural populations that electricity provision might have. Particularly considering the large supply assumed in Chapter 4 for these purposes.

In summary the chapter shows a robust set of considerations for stakeholders' policy generation. The results may create opportunities for modelers and researchers to get involved with stakeholders in further discussion of the tradeoffs, modifications to the model, and extended scenario generation. In this way the work achieves the goal to bridge the gap between system analysis and system guidance through responsible action (Dijkema and Basson 2009).

5.2 Future Work

5.2.1 Additional dynamics and underlying data

The work presented here can be strengthened with better data and easier integration to GIS files, consideration of sectors beyond the residential, and integration of additional social and environmental aspects. GIS layers provide a wealth of information with structured attributes that can be formatted to provide easy interphase. The Netlogo GIS extension takes advantage of these opportunities. While the model was created to use the GIS layers available for Liberia it can be modified so that, with proper formatting and arrangement of the GIS files, any area can be analyzed. This would allow stakeholders to regionalize the tool without the need of investigators.

Data gaps were found in the hydro electric potential and the biomass performance and business aspects in Liberia. Because of their promise to economically fulfill a large portion of the electricity in Liberia these technologies are good candidates for further research. Assessments of the hydrological potential in the country are key for this promising technology to be utilized in Liberia. Biomass potential considered included waste from food and cash crops. There may be competing uses for this waste that need to be included in the model. Liberia has a large potential for forestry products, an industry expected to provide significant economic development in the future (Republic of Liberia 2008). Rubber and palm oil are also expected to experience significant growth over the coming years (Republic of Liberia 2008; Milbrandt 2009). Including these resources, their availability as fuel for biomass generation, and their dynamic growth through the years is key for the model to capture further complementing objectives of economic stimulus and job creation.

The tools presented focus on renewable energy solutions for the residential sectors. Including other consumers of electricity such as the forestry industry, and commercial and service centers would allow a better understanding of the magnitude of possible demand and the required potential for full carbon equality and fuel independence. Critical to the Liberian situation is the supply of electricity to key community services such as schools, medical clinics, government offices, and telecommunications.

While the model is dynamic in nature, it does not capture the possibilities for migration that change the load centers magnitude through time. This is an interesting area of research that could be incorporated for stakeholders to understand solutions to urban crowding and provision of services in remote areas. Literature suggests that the presence of electricity encourages migration to areas with service and reduces migration away from areas that receive it (Andrade and colleagues 2011; Dinkelman 2011). It is also suggested that educated professionals such as teachers, nurses, and doctors avoid areas where basic modern energy services are not met (Modi and colleagues 2005; Andrade and colleagues 2011; Borges da Cunha and colleagues 2007).

A large threat to forests in Liberia comes from the use of charcoal and wood for cooking and heating (Africa Energy Unit 2011). The tools presented here should do a better job in analyzing the co-dependencies between the provision of electricity and reduction in wood and charcoal consumptions. This would allow for a higher relevance in the environmental and human health arenas due to concerns associated with the use of traditional sources of biomass for cooking (International Energy Agency 2010).

5.2.2 Multi-Objective ABM

Competing objectives within an agent and amongst agents can be more deeply explored in the future. This will allow a better connection to policy cases. For instance, in the case of central planning, the Observer Agent can be programmed to include more than two objectives at every time step and to adjust strategies as the model progresses. In the decentralized decision strategy, Agents that represent populations with different preferences can collaborate or compete for the same resources.

Several techniques will be used to design the agents' evaluation methods. Probabilistic or stochastic methods can be used for situations where agents choose between preferences at random. Netlogo and other ABM software packages provide robust tools for stochastic decision-making where an agent can choose from several strategies at each time step at random. The probability of choosing a particular strategy can be adjusted depending on the users desires. For example, the Observer may choose based on economic metrics 50% of time but allow himself to supply electricity to preferred regions the remainder of the time.

Game Theory (GT) can be used for situations where agents are contemplating competition and collaboration in the development of systems with other agents. GT is a formalized study of strategy from the economics field that evaluates the way actors make choices when presented with different situations, or games, and their associated payoffs (Camerer 2003). GT can be embedded within agents (Alfaro and colleagues 2010). It allows the modeling of scenarios in which they compete, cooperate, or collude, under full and incomplete information while seeking selfish or altruistic goals.

Analytic Hierarchical Process (AHP) can be used for situations where agents weigh disparate qualities of a choice. For example different rural electrification models might bring increases in health, decreases in urban migration, improvements in agricultural productivity, and reductions in deforestation. AHP provides a scientific way to arrive at a linear expression for priority setting and decision making simultaneously considering these factors (Mordeson and colleagues 2013). It has already been used in electricity planning efforts in countries like Pakistan and Jordan (Kablan 1997; Amer and Daim 2011). However, incorporating results of AHP surveys and consultations into agents that can capture heterogeneous preferences of different agent groups and their interactions may allow the investigation of emergent behaviors from diversity in ranking preferences. This also allows the disaggregation of data for decision making capturing more of the complexities present between agent interactions in the real system.

By including these different decision mechanisms in the agents, further investigation of the policy planning process can be achieved and more realistic scenarios can be built for the stakeholders to consider. This will require further stakeholder involvement, which will be pursued as described next.

5.2.3 Stakeholder Involvement

Two new paths for stakeholder involvement will be considered, participatory modeling and interactive modeling.

Participatory modeling is a technique where stakeholders, as opposed to a modeler, provide the characteristics and rules of the agents (D'Aquino and colleagues 2003; Aquino and colleagues 2002). They do this through the provision of pseudo code during interviews. Researchers interview the stakeholders that will be represented and convert the interview into actual code for the agents to execute. Through this technique the agents will be able to more realistically represent interactions. For validation and verification, stakeholders can be presented with the model and encouraged to execute model runs and different simulations to ensure that the agents are behaving the way their counter part intended. This also provides transparency for the stakeholders who are able to understand the difference between what their explanation of their decision is and the actual execution of their decision.

Interactive modeling or *participatory simulation* can be used in conjunction with participatory modeling or separate from it. In this technique stakeholders are provided with an interactive ABM that allows them to take control of the agents that are representing them (Guyot and Honiden 2006). This is similar to providing them a video game of their situations. Participants can provide feedback to the modelers for the improvement of the model through their experience. Once a model is refined so that the agents capture the stakeholders' input then policy planning experiments and scenario development can be conducted to study different developments and sectors.

5.2.4 Beyond Electrification

The combination of ABM, decision strategy mechanisms, and stakeholder involvement for policy experiments lends itself for research beyond the electrical systems. In particular the agricultural sector and emerging biomass and biofuels technologies will be targeted for further research. The tools presented here would allow critical examination of new opportunities for LIC to increase agricultural production, stimulate agricultural income, seek climate change resilience, and achieve carbon neutrality and fuel independence.

The underlying concept from Complexity Science of emergence promises further investigations of decentralized solutions to complex and large-scale problems. Water sanitation, food access, and cooking fuel production are services that can be studied under these techniques for the analysis of appropriate mixtures of centralized infrastructure and decentralized provision of services.

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