ARTICLE IN PRESS

Energy Policy xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Improving rural electricity system planning: An agent-based model for stakeholder engagement and decision making

Jose F. Alfaro[a,*], Shelie Miller[a], Jeremiah X. Johnson[a], Rick R. Riolo[b]

[a] Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan, USA
[b] Center for the Study of Complex Systems, University of Michigan, USA

ARTICLE INFO

Keywords:
Developing countries
Agent-based modeling
Policy planning
Rural electrification

ABSTRACT

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

We demonstrate the utility of this approach with a case study based on a "blank-slate" scenario, which begins without generation or transmission infrastructure, for the long-term rural renewable energy plans of Liberia, West Africa. We consider five electrification strategies: prioritizing larger populations, deploying large resources, creating jobs, providing economic stimulus, and step-wise cost minimization. Through the case study we demonstrate how this approach can be used to engage stakeholders, supplement more established energy planning tools, and illustrate the effects of stakeholder decisions and preferences on the performance of the system.

1. Introduction

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

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

In the remainder of this section we offer brief background on energy planning, BABSTER, and the case study of Liberia, West Africa. The Methods section explains the construction of the model, its components, and its dynamics as well as detailed information for the case study analysis. The Results section provides results generated using the model for the case study of Liberia. The Discussion section gives insights into the Liberian case study and also provides an analysis of the use of the model and its possible benefits. We close the paper with a Conclusions and Policy Implications section.

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

1.1. Energy planning

A common approach for long-term electricity planning in developed countries is IRP. It develops a comprehensive plan to meet energy demand by considering available supply and demand side resources

* Corresponding author.
E-mail address: jfalfaro@umich.edu (J.F. Alfaro).

http://dx.doi.org/10.1016/j.enpol.2016.10.020
Received 25 February 2016; Received in revised form 6 October 2016; Accepted 16 October 2016
Available online xxxx
0301-4215/

(Wilson and Biewald, 2013) and minimizing long term electricity costs (D'Sa, 2005). This approach is often data intensive and is mostly done by utility companies regulated by government agencies. Some states in the USA mandate its use and, while not wide spread in developing countries, literature suggests that IRP should be used there as well (Wilson and Biewald, 2013; Suberu et al., 2013).

In LICs, multi governmental organizations, such as the World Bank and the International Renewable Energy Agency, often provide assistance in creating energy plans using diverse modeling techniques. The Africa Energy Unit, part of the World Bank, uses a general algebraic modeling system to analyze two pathways towards electrification in Liberia (Africa Energy Unit, 2011). Their analysis aggregates the larger Liberian electricity needs according to sectors of demand with a medium growth and a high growth scenario. Only certain energy generation technologies are considered and its focus is on the capital city of Monrovia and other select demand points. The results recommend a minimum cost fuel portfolio for each scenario along with the expected cost of electricity and possible supply gaps.

The approach taken by the Africa Energy Unit does not consider the possible contributions of decentralized generation to the general electrification strategy. As the report from the World Bank acknowledges, other efforts are required for the development of a rural electrification program to achieve universal electrification in Liberia according to the goals of the country (Africa Energy Unit, 2011; Republic of Liberia, 2008).

Other modeling techniques have been utilized in developing countries. Urban, Benders, and Moll found 40 different models used for energy planning in developing countries (Urban et al., 2007). However, literature suggests that these energy planning models are biased towards the needs of developed nations and none of the present day models adequately capture the needs of LICs (Urban et al., 2007; Bhattacharyya and Timilsina, 2010). Some of the issues detailed by Urban et al. (2007) are the high data requirements and technical user skills required, lack of sufficient focus on renewable energy technologies and decentralized rural generation options, and the absence of imperfect, non-econometric drivers for decision making. On the other hand Bhattacharyya and Timilsina (2010) point to the need for tools that create scenarios for consideration instead of suggesting one path that should be followed.

Literature suggests that a variety of methods used in conjunction will provide a broader base of data for stakeholders to make decisions and is a better alternative than any single model (Løken, 2007). BABSTER is not intended as a final solution for energy planning in developing countries. Instead, it is offered as a framework for engagement with stakeholders to evaluate possible policies. In particular, this framework can be used as a pre-cursor or supplement to IRP and other more comprehensive exercises. The tool presented here is a good first step towards stakeholder engagement and system understanding while it also attempts to address the issues from Urban et al. (2007), Bhattacharyya and Timilsina (2010) mentioned above.

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

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

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

1.2. Agent-Based Modeling

Analysis of socio-technical systems in which humans interact heavily with technical components has been gaining traction as an application of the field of Complexity Science to different problems (Dijkema and Basson, 2009). Complexity Science seeks to understand how the interactions between small entities can result in the complex macro-scale behavior of systems that in some cases, learn, adapt, and evolve (Mitchell, 2009).

Agent-Based Modeling (ABM) is a platform useful for socio-technical systems (van Dam et al., 2013). ABM conceptualizes the components of a system and their interactions instead of producing a macro-level mathematical model. To do this, computer "agents" are created that represent the small level components of the system. They are placed in a computer environment or "world" and are provided with rules to interact with each other and their environment.

ABM should not be used as a predictive tool but as a scenario generation package (Kraines and Wallace, 2006). Policies and stakeholder preferences can be easily introduced into ABM as exogenous rules for the agents to create simulations of interest. In this way, ABM can mimic stakeholder inputs (DeLaurentis and Ayyalasomayajula, 2009), allowing practitioners to include the social context in which systems are evolving and making it a low cost test bed for policy and planning scenarios (Axtell et al., 2002). The simulations allow "*in-silico"* experiments impossible to conduct on the real system.

1.3. Liberian case study

As of the census of 2008, Liberia, West Africa, has a population of 3.47 million people, over 70% of them in rural areas (Republic of Liberia, 2009). The country has an area of 111,370 km^2 (Hamdan, 2010). Less than 1% of the population in Liberia has access to electricity, paying the highest rate in the Sub-Saharan region, at $0.43/kWh (Africa Energy Unit, 2011). A central grid serves the capital city of Monrovia through high-speed diesel generation (Africa Energy Unit, 2011). New projects are being pursued that intend to expand the country's electricity grid through increased diesel generation, refurbishing a heavy fuel oil facility, reconstructing a hydroelectric facility, and connecting to the Western Africa Power Pool (WAPP) (Africa Energy Unit, 2011). Even with successful implementation of these projects, more than 50% of the rural population in Liberia is not expected to have access to electricity by the year 2040 (Africa Energy Unit, 2011). The proposed projects depend largely on fossil fuels, a centralized structure, and reliance on the WAPP. Pineau has questioned the possible success of the WAPP as it requires a level of collaboration among nations in the region that has not been successful among other regions of the world with more developed energy infrastructure and higher institutional capacity (Pineau, 2008).

The government of Liberia has issued policies that support additional electrification efforts beyond the centralized scheme. The National Energy Policy issued in 2009 proposes the goal of universal access to modern energy services in the country (Ministry of Lands Mines and Energy, 2009). The Rural Renewable Energy Agency (RREA) was established in 2010 (Africa Energy Unit, 2011). RREA is charged with administering the electrification of the rural areas using modern energy services (RREA, 2015). RREA is in the process of establishing a rural electrification master plan. BABSTER could serve to facilitate the beginning stages of this process and encourage