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Design of decentralized biopower generation and distribution system for developing countries

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ABSTRACT

This paper presents a general decentralized energy generation optimization model for developing countries. A mixed integer nonlinear programming model has been formulated and implemented, representing decisions regarding (1) the optimal number, locations, and sizes of various types of processing plants, (2) the amounts of biomass transported, and electricity to be transmitted between the selected locations over a selected period, and minimizes the objective function of overall generation cost. The model has been applied first for designing a decentralized energy generation system using palm oil biomass for Iskandar Malaysia region of the state of Johor, Malaysia and then extended to entire state. We investigated the benefits of more distributed types of processing networks, in terms of the overall economics and the robustness to demand variations. No change in designed decentralized energy generation system and distribution network was observed when the demand was lowered to 90%, 75% and 60% of original demand.

1. Introduction

Rising concern about the effect of greenhouse gas emissions on climate change is pushing national governments and the international community to achieve sustainable development in an economy that is less dependent on carbon emitting activities is a vision that is usually termed a “low-carbon society”. Electricity is conceivably the most multipurpose energy carrier in modern global economy, and therefore primarily linked to human and economic development as well as the environment. Energy sector reform is critical to sustainable energy development. Global dependence on fossil fuels has led to the release of over 1100 Gt CO_2 into the atmosphere since the mid-19th century. Currently, energy-related greenhouse gas emissions, mainly from fossil fuel combustion for heat supply, electricity generation and transport, account for around 70% of total emissions including carbon dioxide, methane and some traces of nitrous oxide. This multitude of aspects play a role in societal debate in comparing electricity generating and supply options, such as cost, greenhouse gas emissions, radiological and toxicological exposure, occupational health and safety, employment, domestic energy security, and social impressions (Bazmi and Zahedi, 2011; Bhutto et al., 2014). Through the different stages of development, humankind has experimented with various sources of energy ranging from wood, coal, oil and petroleum to nuclear power. In recent years, public and political sensitivities to environmental issues and energy security have led to the promotion of renewable energy resources.

Better access to modern energy sources and electricity is an obligatory for improving living standards and reducing poverty in rural areas of developing countries. Currently over 1.6 billion people (85% of the world population) living in rural areas have no access to electricity (Levin and Thomas, 2012). Electrification rates in rural areas of developing countries are substantially low. Even when electricity supply is available, the service is unreliable and expensive. The electricity issue in rural areas cannot be solved as a simple problem of demand and supply or as a mere logistic problem to provide electricity services (Abe et al., 2007; Bouffaron et al., 2012; Gmünder et al., 2010; Ravindranath, 1993; V. Siemons, 2001). There is significant debate over the best means to carry out the electrification process. Most developed countries rely on a centralized electricity generation and distribution system.

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Electricity is generated at scale in large central plants and then distributed to end users through a transmission network. These networks can be expensive and in most cases take many years or decades to fully develop. Also these centralized energy supply systems are losing its attractiveness due to a number of further annoying factors including the depletion of fossil fuels and their climate change impact, the insecurities affecting energy transportation infrastructure, and the desire of investors to minimize risks through the deployment of smaller-scale, modular generation and transmission systems (Bazmi et al., 2011). An alternative for electrification of rural and remote areas is the introduction of decentralized conversion technologies using resources locally available. Decentralized electrification can provide a more reliable supply and generate income derived from the use of local resources (Grassi and Bridgwater, 1993; Herran and Nakata, 2012; Obernberger, 1998; Ravindranath, 1993; Senelwa and Sims, 1999).

Decentralized electrification using local resources can reduce regional disparity in rural and remote areas in terms of supply reliability and cost, as well as promote income generation. Humans constitutes an important element of every complex socio technical systems (Besnard and Hollnagel, 2014; Nazir et al., 2014), which cannot be ignored in case of decentralized energy. In fact, in decentralized energy systems, the human is not only an end-user but his/her involvement in defining the relevant policies may impact the possible benefits of decentralized energy philosophy (Perc et al., 2013; Perc and Szolnoki, 2010). A careful social impact-assessment showed that the decentralized energy systems opened a social as well as micro-economic dilemma and the acceptance and adoptability of distributed networks in developing countries is still debatable as a social dilemma and human cooperation. Evolutionary game theory provides a competent theoretical framework for addressing the subtleties of cooperation in such situations, which are known as social dilemmas. Recent advances point towards the fact that the evolution of strategies alone may be insufficient to fully exploit the benefits offered by cooperative behavior. Co-evolutionary rules can extend the potentials of such entities further, and even more importantly, lead to the understanding of their emergence. Local conditions, social and political power relations and economic circumstances must first be analyzed in depth, before a project is implemented (Perc and Szolnoki, 2010). One crucial fact remains, though: regardless of who owns which part of the system, a consistent, cheaper and large enough amount of energy might arrive in rural communities. This human element cannot be overlooked in realization of how a decentralized biopower generation and distribution system could lead to a long-term sustainable future in the rapidly developing parts world, however, in this preliminary stage of the proposed mathematical model such policy matters are not considered.

This study focuses on the decentralized electricity generation (DEG) from biomass and the distribution network. One of the most important and challenging aspects of DEG is the design and operation of biomass and biopower supply chain networks. Supply chain modeling and supply chain system optimization have received a lot of attention among companies and academic research groups alike in recent years (Bazmi and Zahedi, 2011). Several models and solutions that can be used as decision support tools for strategic analysis as well as tactical planning of the energy systems have been proposed. But no remarkable work has been done for decentralized bio-power systems. This paper presents a general decentralized energy optimization model for developing countries that enables the selection of biomass conversion technologies, capacities, biomass conversion plant locations, and the logistics of transportation from the biomass sites to the conversion sites and then to deliver electricity to specific demand locations.

2. Background

Access to electricity is an important component of rural development. Better access to electricity has been correlated to the improvement of living conditions in several aspects, such as education and income generation. Electrification in rural areas of developing countries, and in particular in the case of remote areas, is difficult due to low population densities, highly dispersed location of populated centers, low energy consumption levels per capita and poor road infrastructure which constrains transportation. This makes conventional rural electrification programs based on extension of the electricity grid and decentralized schemes with foreign fuels expensive or even economically not feasible. Rural electrification programs often require direct governmental support in the form of subsidies. In rural areas where energy resources are widely available in the form of agricultural wastes and forest biomass, DEG using local resources is more suitable as an alternative for electrification. DEG avoids the necessity of extending transmission lines to dispersed populated centers, reduces the dependence on foreign fuels within these areas, and promotes local development through the introduction of the production chain of biomass energy (Herran and Nakata, 2012). Biomass is one such resource that could play a substantial role in a more diverse and sustainable energy mix (Bhutto et al., 2011). Biomass, a major source of energy in the world until before industrialization when fossil fuels become dominant, appears an important renewable source of energy and researches have proven from time to time its viability for large-scale production (Bazmi et al., 2011). DEG utilizing biomass is gaining increasing interest for electrification for rural areas in developing countries. A lot of studies have been made in last two decades to assess and implement decentralized power systems including the literature dealing with energy planning supported by mathematical models (Bazmi et al., 2011). Most models applied for designing decentralized energy systems describe the optimal mix of energy resources and technologies under a certain objective function and set of constraints. The analytical approach generally used in these models is single-period optimization (Ashok, 2007; Karki et al., 2008). In addition to optimization, there are studies deploying simulation and geographic information systems methodologies that give more emphasis to supply stability and optimal allocation of resources (Nfah et al., 2007; Underwood et al., 2007; Yue and Wang, 2006). Decentralized energy systems have also been designed by means of multi-criteria and multi-objective methodologies (Cherni et al., 2007; Chetty and Subramanian, 1988; Kanniappan and Ramachandran, 2000; Pohekar and Ramachandran, 2004; Silva and Nakata, 2009, 2008). A more comprehensive review of model applications for designing rural energy systems is provided by Nakata et al. (Nakata et al., 2011). Recently, (Herran and Nakata, 2012) designed decentralized energy systems for rural electrification in developing countries using LP optimization model. In this only available research on decentralized energy system for biomass utilization, authors focused on the regional disparity incorporated by disaggregating electricity demand into urban, rural and remote areas. It is worth noting that among these studies complete assessment of DEG encompassing from source renewable energy fuel, technology selection, optimal site selection, market assessment and distribution network for final product; electricity is not yet explored. This paper suggests a complete DEG system for biopower with distribution network. The model is formulated as mixed integer nonlinear programing (MINLP) optimization problem. The MINLP represents decisions regarding (1) the optimal number, locations, and sizes of various types of processing plants, (2) the amounts of biomass transported, and electricity to be