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Original Research Article

Economic and environmental assessment of renewable energy micro-systems in a developing country

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ABSTRACT

This paper intends to evaluate the impact of the introduction of electricity generation micro-systems based on 100% renewable sources to supply electricity demands of non-electrified rural residential houses in Santiago Island's energy system (Cape Verde). For that purpose a comparison between three energy scenarios (2011–2030) were studied: a Reference Scenario, where it was assumed that the electricity grid would be expanded to increase households electrification rate and that grid connected renewable energy technologies will be used to increase generation power; a Diesel Scenario, where future electricity requirements would be provided by constructing new diesel power plants; and a Decentralized Scenario that is based on the Reference Scenario but that differs from it for the fact that it considers the installation of off-grid renewable energy micro systems (REMS) to attend electricity requirements of post-2010 electrified rural houses. The electricity supply–demand system of Santiago Island was modeled using an energy planning software and an optimal REMS design was modeled to provide electricity requirements of a typical Santiago's household. Although it is clear that using renewable energy technologies (Reference Scenario) presents better results from an environmental and economical point of view than installing new diesel power plants (Diesel Scenario), using off-grid REMS to electrify post-2010 rural households (Decentralized Scenario) result to be even more beneficial than generate and distribute on-grid renewable electricity.

Introduction

Energy consumption is fundamental to sustain modern societies. It is needed to fulfil population's basic needs and to supply productive systems with the required power and heat. Over the years potential scarcity on energy resources has been solved by developing and using better technology to extract them. For a long period of time, per capita energy consumption was, in fact, a measure of nation prosperity: more energy used, more developed the nation would be. Energy planning could be summarized as the task of assuring supply of the correct amount of energy, on time and as inexpensive as possible [1,2].

The 1970's energy crisis changed that way of thinking: sources of fossil fuels were not as abundant, as available and as cheap as it was thought [3]. Simultaneously, environmental and social issues started to arise, namely the environmental degradation which is an outcome of burning fossil fuels and its effect on human health [4]. Bottom line, economic criteria could not be sufficient to properly perform on energy planning. Energy planning must account for [4,5]:

- *Economic criteria:* Investment and operational costs.
- *Technical criteria:* Efficiency, Feasibility, Safety.
- *Environmental criteria:* Air pollution, resources scarcity, impacts on ecological habitats.
- *Social criteria:* Employment, Public acceptance, Public health.

Because testing and experimenting in real world situations is most of the times impractical, too expensive or impossible, energy models can be used to perform comprehensive calculations and system analysis in simplified representations of real systems. Jebaraj and Iniyan [6] studied a large variety of energy models, and grouped them in five categories: supply–demand models, forecasting models, optimization models, neural-network models, and emission models. Hiremath et al. [7] reviewed the use of energy models to perform decentralized energy planning and the integration of renewable sources of energy. The authors classified energy

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models as: optimization models, energy supply/demand driven models, resource energy planning models, and energy models based on neural networks. Urban et al. [8] approached the particularity of energy planning in developing countries, and studied the suitability of current energy tools to address the planning problems of those countries.

Using computer models to perform such experiments offers great advantages: it allows to explicitly state the assumptions that form the base of the model; the logical consequences of the modelers' assumptions are computed; many factors can be inter related simultaneously. Although some of the computer programs were developed for a specific energy system analysis, it is time-consuming to create new tools for each and every analysis. In that sense, several software tools were developed and used to create a model of any given energy system. Depending on the purpose of the analysis to be conducted, a suitable software tool must be selected. Connolly et al. [9] reviewed a large set of computer tools (37 to be precise) that could be used for energy planning allowing the integration of renewable energy into energy systems that would help the selection process of the "ideal" software for a specific situation and objectives.

Because of their economical, political and even geographical characteristics, developing countries' energy systems have specific features and obey to a particular rationality. This is even more perceived in islands due to their isolation, the lack of conventional energy sources and the small dimension of their energy market. Renewable energy systems (RES) have been presented as an interesting solution to provide electricity to isolated islands or remote villages [10]. A significant number of research papers that have addressed different RES configuration has been exploited. Some examples: stand-alone photovoltaic system [11]; a combined cooling, heating and power hybrid system [12]; a HES (Hybrid Energy System) comprised of photovoltaic panels and wind turbines grid-connected [13] or stand-alone [14]; and even wave energy systems have been studied [15]. While most of the research papers address the implementation of RES at a village and/or island scale, using individual house-level renewable energy micro systems (REMS) is also an alternative: a World Bank report [16] advocates the photovoltaic-diesel generator system as a good solution where customers are few and dispersed and their main electricity use is domestic lighting; in Peru, individual solar home systems were chosen as the T by the ACCIONA Microenergy Foundation (FUNDAME) to facilitate access to basic electricity services to rural communities with no expectation to get electricity networks [17]; for the rural Pacific island of 'O'ua, which is part of the Ha'apai Solar Electrification Project in Tonga, it was determined using least-cost analysis that solar home systems would provide the most cost-effective means of supplying electricity when compared with a village diesel generator for supplying basic household electricity services [18].

Cape Verde (a cluster of ten islands located on the North Africa's west coast) is one of the smallest and poorest "small island developing states" (SIDS) and has been used as case study in different analyses. Monteiro et al. [19] studied and analyzed the success of using renewable energy technologies in Santo Antão, a Cape Verde island. Their intention was to identify the best strategies for optimizing the energy supply mix in Cape Verde Islands. Duic et al. [20] analyzed different scenarios for the development of the Santiago Island's electricity system and studied how the Kyoto Protocol, through the Clean Development Mechanism, could influence the transfer of clean energy technologies. They concluded that although Santiago Island's electricity generation is heavily dependent on Diesel engines, expensive and polluting, it's still the most appropriate on such a small scale. The paper also shows that although the emission reduction on global scale is small, there is great potential for establishing a strong market presence of renewable energy technologies in developing countries. The H_2RES model was used to design and analyze different scenarios with the objective of maximizing the penetration of renewable energies in the energy system of S. Vicente Island in Cape Verde [21]. The results show that it is possible to have more than 30% of yearly penetration of renewable energy sources in the electricity supply system, together with more than 50% of the water supplied to the population produced from wind electricity.

The purpose of this study is to assess, both economically and environmentally, the impact of a decentralized electrification plan, based on the expansion of electricity supply by installing renewable energy micro-systems (REMS) in a developing country (Santiago Island, Cape Verde). The following section will present the methodology used to perform the analysis. Santiago Island's electrical system and an optimal renewable energy micro system (REMS) to provide electricity requirements of a typical Santiago's household are designed and presented in 'Modeling Santiago Island Electricity System' and 'Design of a renewable energy Micro system (REMS) for a typical Santiago Island household' respectively. 'Santiago Island Energy Scenarios' will present the assumptions used to develop three different scenarios for the development of Santiago's electrical system. The results of both models and the analysis of the outcomes of all three scenarios will be debated on 'Results'. And, finally, conclusions will be pointed in 'Conclusion' of this paper.

Methodology

Connolly classified energy computer tools according to different criteria: type of calculations allowed by the tool (simulation, optimization, scenario analysis, etc.); the geographical area analyzed by the tool (global, national, regional, local, community); or the energy sectors included (transport, electricity, heat). To accomplish the purpose of this study the electricity system of Santiago Island must be simulated, an optimal REMS should be designed to attend the electricity requirements of a typical Santiago house, and the impact on the Santiago electricity system of introducing the optimal REMS design in several houses on the island must be assessed. By analyzing Connolly's review and having in mind the specific purpose of this paper, it was clear that a single software was not able to perform the analysis required: a simulation and scenario analysis at national level and an optimization analysis to a local level. Two software tools were used on this paper and a visual description of how the two software tools were integrated and used is presented in Fig. 1.

Long-range Energy Alternative Planning (LEAP) [22] uses an annual time-step, and the time horizon can extend for an unlimited number of years (typically between 20 and 50). It supports a number of different modeling methodologies: on the demand-side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling; on the supply side, it provides a range of accounting and simulation methodologies for modeling electricity generation and capacity expansion planning. LEAP can simulate all sectors, all technologies, and all costs within an energy-system, as well as externalities for any pollutants, decommissioning costs, and unmet demand costs. LEAP also includes a scenario manager that can be used to describe individual policy measures. The resulting scenarios are self-consistent storylines of how an energy-system might evolve over time. LEAP displays its results as charts, tables, and maps which are user-defined and can be exported to Excel or PowerPoint. LEAP was used in this paper with two main purposes: (1) to design the electricity demand–supply system model of Santiago Island; (2) to develop three different scenarios for the energy model evolution, for a 20-year time horizon.