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A dynamic simulation of low-carbon policy influences on endogenous electricity demand in an isolated island system

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ABSTRACT

This paper considers the dynamics of electricity demand in response to changes arising from low-carbon policies and socio-economic developments. As part of an investigation into the evolution of such systems on small economically-developed islands, endogenous electricity demand and associated policies are studied for the Azorean island of São Miguel. A comprehensive *System Dynamics* (SD) model covering the period 2005 – 2050 is presented which captures both historical behaviours and real-world influences on the endogenous demand dynamics of an island-based electricity system. The impact of tourism, energy efficiency and *electric vehicles* (EV) expansion allied with associated policy options, are critically evaluated by the SD model using a series of scenarios. The model shows that energy efficiency measures exhibit the most significant long-term impact on electricity demand, while in contrast, policies to increase tourism have a much less direct impact and EV expansion has thought-provoking impacts on the long-term demand, although this is not as influential as energy efficiency measures.

1. Introduction

Policy makers worldwide are attempting to reduce the emission of harmful greenhouse gases produced during electricity generation, while simultaneously either preserving or enhancing energy security. This challenge is compounded by the desire to achieve the required changes without greatly increasing economic costs which would risk an erosion of national economic competitiveness. For large electricity systems such as for a major country or continent, the inherent system complexities present an intractable challenge (Bompard et al., 2012), so a more pragmatic option is to consider a smaller, but nevertheless complete, autonomous electricity system as the case study. It is in this context that this paper focuses on a specific island-based electricity system, namely that of São Miguel in the Azores.

São Miguel has a set of attributes which make it particularly attractive for this case study:

- It is part of Portugal in the European Union and it is economically developed.
- It is of sufficient size and complexity to emulate the attributes of larger systems.
- It has neither electrical connections to any other island nor to the mainland.
- While the island has some political autonomy, electricity prices are not set locally but are determined administratively in Lisbon, so the electricity system on the island is not economically isolated (EDA, 2008).

Economically developed island systems differ from similarly prosperous larger scale systems in that they generally do not endogenously develop new technologies. They lack size and complexity and are too small for effective economic competition when considering more sustainable future pathways (Eurelectric, 2012). They also do not usually have local price formation so electricity prices can be modelled as an exogenous variable, largely independent of local economic conditions. The electricity provision for island systems has historically been dominated by a dependency on imported, heavy fuel oil and diesel, and as a consequence, the energy system, and the island's economic growth, have been linked to fossil fuel prices. The literature suggests that typical small island consumers and stakeholders have no power to influence such fuel prices as they are exogenous to the island, even though they are politically semi-autonomous (EDA, 2008; ERSE, 2014, 2012).

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Furthermore, there is growing evidence that it is important to understand the key lessons that allow smaller semi-autonomous systems to become sustainable and then to extend them to larger networks (Ilic et al., 2013). As a result, these systems offer an ideal testbed to investigate endogenous demand dynamics and renewables penetration (Eurelectric, 2012). For example, Weisser (2004) examined the main economic and technological obstacles for incorporating renewables within small island systems, while (Ilic et al., 2013; Parness, 2007; Pina et al., 2012) studied such testbed systems. However, they did not consider endogenous demand dynamics and complexity, but instead principally focused on economic and/or technical provisions for demand within these systems.

However, other studies including (Jordan, 2013; Steel, 2008) suggest that demand dynamics cannot be ignored, being inexorably tied to the structure of the system. Indeed, an understanding of demand dynamics can reveal unexpected causal behaviours leading to new policies, and hence useful sustainability guidelines for the future. *System dynamics* (SD) (Forrester, 1961; Sterman, 2000) affords a methodology for understanding the structure of an island electricity system and its response to policies using a micro-world model (Morecroft, 1988). SD offers a platform for novel endogenous modelling of the demand dynamics of an island electricity system and in identifying the most important and influential energy policies that may impact upon long-term demand within the system.

In this paper, the long-term endogenous electricity demand of São Miguel is modelled to derive a better understanding of the inherent dynamics of the future demand within an island context. Importantly, the Azorean islands have already been extensively studied over the last decade by researchers from MIT and Carnegie Mellon University, together with Portuguese academic collaborators and the Portuguese Government as “a living laboratory” for sustainable energy solutions (MIT-Portugal, 2013). This has led to a rich repository of available data for further studies. A new SD model has been developed to exploit this relevant historical data using realistic responses of investors and consumers to policy drivers and system variables. An SD model can characterise the most important feedbacks and causal relations, together with the stock and flow structures within a system. The model was used to obtain a rigorous knowledge of the key demand dynamics and to evaluate policies and their implications for the development of the island's electricity system. It studied policies that facilitate low-carbon systems, whilst ensuring the security of the electricity supply. Hence, insights into the effects of key policies on the structure and dynamical behaviour of the evolving endogenous electricity demand within island electricity systems were provided.

The future demand dynamics of the system have been analysed based on three independent policy drivers highlighted by (Bothelo, 2015; Eurelectric, 2012; Nunes, 2015): These are (a) Electrification via *electric vehicles* (EV); since this is a focus of island systems for increasing the low demand during night-time periods. (b) The effects of energy efficiency; viewed as essential to ensure energy security. (c) The influence of tourism; since island systems are concerned about the impact on their electricity systems of a fluctuating number of visitors (European Commission, 2013). Assorted scenarios are critically analysed which emphasise in turn, each of these policy drivers, and gauge the most important and interesting ones to policymakers, for meeting long-term electricity supply security and environmental concerns. The SD model also details the priority policy areas and determines whether long-term system responses may be counter-intuitive as the island pursues exogenous and politically-driven low-carbon policies. The next section presents the background to the low-carbon issues and challenges and the inherent types of policies and strategies used in island electricity systems.

2. Energy policy and strategy for island systems

Island systems have traditionally been heavily reliant on fossil fuels, with the main issues being high and volatile fuel costs and the limited scale for cheaper fossil fuel generation options such as coal and natural gas. The drive towards low-carbon objectives, while remaining flexible and reducing the dependency on expensive oil imports has created a strong economic incentive to change the system's status quo (Eurelectric, 2012). While the use of renewable energy sources avoids future unknown fuel costs and associated risks, there is the risk of high upfront capital costs. This may be absorbed by the mainland, such as in this case study, via economic and policy links, whilst ensuring the long-term security of the electricity supply for meeting the demand.

However, apart from costs, there are other emerging issues such as the nexus between reliability and availability of renewables, and the sustainability and economic stability they can provide for the electricity demand. Most renewables are not base-load which can give rise to concerns over the supply security of such systems. Barrett (2006) and Warren (2014) highlighted possible general solutions to these security challenges including building new capacity (a costly venture due to the infrequent peak time users they can command); increasing interconnections with other countries (restrictive especially for geographically isolated islands); developing and using large-scale energy storage technologies (an immature solution which is very expensive); location-dependent pumped hydro systems (not always feasible to build); and demand-side management (currently a theoretically rich but practically limited solution). These low-carbon objectives and considerations give rise to the added system complexity and highlight the need, and opportunity, to gain insights into the long-term endogenous evolution of electricity demand.

For island systems, the challenges are greater since they may be unable to make use of mainland solutions as suggested by Barrett (2006) and Warren (2014). These electricity systems face great uncertainty in their demand with proportionally large daily and seasonal variations. The variations can be further perturbed by small changes in efficiency measures, economic activity, and consumption patterns, without the benefits of large system balancing area, smoothing effects. These issues are highlighted in (Eurelectric, 2012) where the authors detail an overview charter towards a sustainable island energy future. In São Miguel, for example, consumption has a demand curve trough during the night, of approximately 50–60% of the peak daytime consumption (EDA, 2016; ISLE-PACT, 2012). This large discrepancy contributes to hindering the advent of more renewables, and the low-carbon agenda because fossil fuels are needed for the peaking demand in the day and also throughout the night for stabilising the power system frequency. However, policy emphasis on the electrification of the transport sector, through the encouragement of light-duty, EVs on the island, provides an opportunity to raise the level of the night-time trough, allowing for more renewables capacity and helping to further mitigate CO_2 emissions (Bothelo, 2015). Implications for the island's electricity demand policies are thus far reaching, and clarity is required in prioritising important policy decisions to shape a secure and sustainable future for island electricity systems.

For example, there is the issue of unnecessarily increasing the generation capacity on an island electricity system, which was a strategy proposed by Barrett (2006) and Warren (2014). Given that economically-developed island, systems are already endowed with high levels of reserve legacy fossil-based capacity, further large-scale investments in either fossil fuel or renewables capacity may not be justified given the amount of latent capacity available (EDA, 2016). This excess capacity is however required to maintain reliability and some security of supply, by providing a wider range of electricity production units (there is usually a preference for several smaller generation units instead of one large generator). The electricity provider in São Miguel estimates that capacity margins are above 30% so the impetus for renewables is more focused on reducing CO_2 emissions and on achieving fuel independence (EDA, 2016). Meeting energy security concerns by building new capacity is not advisable unless this is coupled to the aim of replacing decommissioned fossil generation with renewable sources.