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

Energy Policy

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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.

Keywords: Endogenous electricity demand; Island electricity systems; System dynamics; Electric-vehicles expansion; Energy efficiency; Tourism

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 semiautonomous (EDA, 2008; ERSE, 2014, 2012).

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 CO₂ 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 CO₂ 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.

Another alternative mainland solution, (Eurelectric, 2012) is the concept of inter-island grid interconnectivity. However, this is infeasible in most cases, since the island systems are almost always geographically too distant for economic interconnections. Also given considerations are the prospects of demand-side management and large-scale pumped hydro energy storage (Barrett, 2006; Eurelectric, 2012; Warren, 2014). Demand-side management considered here is not the explicit real-time matching of demand to the available supply with automated load-

shifting mechanisms (Warren, 2014). However, this is considered as the charging of EVs during periods of low electricity demand. The prospect for pumped-hydro storage is also limited due to the geographical constraints of most small island systems. For example, the energy company in São Miguel has undertaken evaluation studies into the siting of a pumped-hydro project and concluded that no suitable conditions exist for the required dams but that smaller reservoir storage is possible (Bothelo, 2015). However, there is a need for island electricity systems to adopt low-carbon energy-related policies and solutions to explore the impacts of changing economy-driven products such as tourism. (Haney et al. 2010) postulate that low-carbon energy policies support a means of reduced electricity consumption through energy efficiency policies and demand-response/demand-side management mechanisms. Similarly, the International Energy Agency (IEA, 2008) identified a trend towards increasing energy efficiency measures as an essential element in overcoming the challenges facing the energy sector. While true for large interconnected systems, it has not been proven for small-island systems, where the focus is to maximize electrification, via the use of EVs, while minimizing the curtailment of the installed intermittent renewable capacity and increasing their economy-driven products such as tourism (European Commission, 2013).

Recent studies promote the electrification of the global transportation sector as a means of adding further renewables capacity and enhancing the long-term security of the electricity supply (Aghaei et al., 2016; Kintner-Meyer et al., 2007; Paterakis and Gibescu, 2016; Shokrzadeh and Bibeau, 2016). Current island electricity system research suggests that this also holds within these systems (Baptista et al., 2009; IEA, 2013; Parness, 2007). The authors highlight that accelerated adoption of EV can facilitate the quick removal of fossil generation in smaller isolated systems by matching the renewable-based supply with the demand. A policy favouring EV thus provides the opportunity to operate the vehicles principally on renewables that would have otherwise been curtailed when the demand load is low i.e., at night-time. While

a minimal technical amount of fossil generation will be necessary to balance the frequency of the electricity system, the energy capacity released from the renewables can be used to charge the EVs to eliminate the problem. The potential environmental benefits are significant including a diminished need for fossil fuel to run cars and power generators which also satisfies the low-carbon agenda whilst ensuring the security of the electricity supply to meet the long-term demand dynamics.

Baptista et al. (2009) used São Miguel to analyse the impact of introducing EVs, applying a short-term discrete scenario-based life-cycle approach to quantify their impact on the demand and CO₂ emissions. Crucially this analysis did not extend to considering longer-term system factors, hence a key motivation behind this paper is to investigate further using the SD methodology for an island system, to provide the necessary understanding and insights, given its ability to reflect long-term demand dynamics and policy impacts on electricity systems (Ford, 1997; Jordan, 2013; POLES, 2016; Steel, 2008). Furthermore, SD has previously been applied to address many aspects of energy policy from the past and present electricity grid systems including capacity planning, operating investments, electricity market simulations, balancing of fuel/technology mixes for grid system performances and electrification using EV (Arango et al., 2002; Caravajal et al., 2011; Ford, 1997; Jordan, 2013; Sanchez et al., 2007; Teufel et al., 2013). An SD methodology has not previously been adopted to analyse a small island endogenous electricity demand. Previous energy policy studies conducted on islands like the Azores include, TIMES MARKAL models for demand-side management strategies (Pina et al., 2012), a least-cost unit-commitment model analysis to determine the expected cost savings from introducing energy storage into existing electrical power grid networks (Cross-Call, 2013), and multi-criteria decision methods to compare energy storage and other planning options for sustainable development (Silva, 2013). Additionally, Parness, (2007), made use of an economic dispatch and unit-commitment model to explore the environmental sustainability

options on São Miguel, focusing on the optimal charging strategies for EVs needed to reduce electricity and transportation costs and minimize CO₂ emissions. Collectively, these studies do not reflect endogenous demand dynamics of the system but do include the use of exogenous demand growth. This paper, therefore, focuses on making the demand dynamics endogenous to provide stakeholder insights into the emerging system characteristics and ultimately leading to more informed policy decisions to satisfy evolving demand.

The new SD model captures the endogenous demand dynamics of the system for various scenarios, including energy efficiency, electrification, and tourism, to identify which are most important as the island pursues environmental objectives and supply security. It is distinct from (Matthew et al., 2016, 2015) and (Balnac et al., 2009), which also used SD studies of an island electricity system. Balnac et al. (2009) used Threshold-21 (T21) for applying SD to aid policy-making in an integrated manner on the island of Mauritius. Although supply and demand were endogenous to their model, it assumed a least-cost-first rule for allocating demand to the different generating sets and also did not provide a resolution about the structure of the different sectors of electricity consumption and the relevant energy policies. The key to the new SD model is the structure of the demand sectors and the high level of endogeneity exhibited by the demand of the system. (Matthew et al., 2016, 2015) which were built to consider the investment criteria for fossil-based island systems and the influences of learning curves on renewables integration within such systems. Additionally, these models used an exogenous data extrapolation of the island demand, while the new São Miguel SD model aims to define the long-term endogenous demand and to elicit the most important and influential policies given the emerging trends and challenges from the environmental and energy security concerns. Details of the model are presented in the next section.

3. Electricity demand model

The case study with the necessary attributes highlighted for this work is the island of São Miguel. It is a part of the archipelago of nine Portuguese islands about 1,500 km west of mainland Portugal within the Atlantic Ocean. São Miguel is the largest island in the Azores, both in terms of size - 744.55 Km² and population -140,000 inhabitants. The main electricity utility in São Miguel, Electricidade dos Açores (EDA), serves all nine islands as a fully regulated utility with a few independent power producers which sell their electricity (less than 2% of total production) to the EDA utility (EDA, 2016). Electricity customers pay the same retail prices rates as mainland Portugal according to national law, so tariffs are effectively subsidized by the rest of Portugal (Cross-Call, 2013). For EDA, electricity consumption can be allocated to consumer types of residential, commercial services, industrial and public services (EDA, 2016, 2008). EDA statistics from 2005 to 2015 show that residential and commercial services make up approximately 30-35% respectively of the total demand. Public services have a share of about 15% while industrial demand stands at approximately 20% of the total. Additionally, the daily load duration curves have loads between 70 and 30 MW for the vast majority of hours in 2015 (EDA, 2016). According to (ERSE, 2014, 2012), the annual electricity consumption grew by more than 3% a year for the 5 years prior to 2014 and future demand is expected to rise by similar margins. Furthermore, the island *Gross Domestic Product* (GDP) has grown by an average of 2% per year since 2005 (European Commission, 2013), signalling optimism within the electricity consumption growth forecast. Also embedded in the framework is the political oversight by the Regional Directorate for Energy which is tasked with overseeing the promotion and execution of sustainable and environment-friendly energy systems.

3.1. Model Structure

An SD model of the island electricity system has been developed to evaluate the influence on demand of different policy options. A scenario-based method has been employed, in which different set-ups are independently investigated, in line with the three policy options identified in Section 4. For each scenario, the model is simulated on a monthly time-step over a 45 years' time horizon from 2005 until 2050, with the goal of studying the average long-term and endogenous electricity demand.

Each sector of electricity consumption is modelled independently in its entirety (which includes the energy efficiency policy implementations) and then all the sectors are aggregated to obtain the total system demand. Residential consumption is modelled in terms of birth, deaths, and migration, together with the *standard-of-living index* (World Bank, 2016) as a proxy for the demand-growth per household. The commercial services sector take account of the growth-rate in the monthly average number of night stays resulting from tourism and its influence on the consumption in this sector. It also captures influences of the exogenous GDP change for new commercial services consumption. The industrial sector captures the number of changing industries as influenced by the exogenous GDP growth and the resulting industrial consumption growth rate. The public services sector reflects influences of the external GDP on the public services consumption growth rate. The contribution to total demand from EVs is implemented with inputs from the EV policy, its enactment year and duration. Additionally, it is continuously verified that this desired number satisfies the long-term supply versus demand mismatch, and the short term day/night hourly demand imbalance. This day/night hourly demand imbalance is determined by using the hourly demand for all months within the years 2013-2015 (Bothelo, 2015). Using this hourly data from each month, the minimum and maximum hourly demand values are determined and the differences are calculated. The

respective differences of the minimum and maximum demand for each month are then normalised using the maximum hourly demand occurring within that month. This is implemented as a pre-processing step prior to the model simulation and a normalised minimum/maximum profile is built from the 1095 data pairs (i.e. daily pairs spanning the three year period). The data points are randomly chosen during simulations for determining the threshold amount of EVs necessary to handle the day/night hourly demand imbalance.

The main components of the model are the consumer sectors of the electricity consumption (which includes EV adoption), the energy efficiency policy influences, and some supply and energy-storage aspects based on exogenous capacity portfolios (fractional percentage of the total installed capacity) determined by the current renewables and energy-storage policies. Figure 1 illustrates the mental model of the complete system which comprises three main feedback loops. As defined in the SD methodology, it is a high-level causal diagram, summarising the main feedback loops captured by the model and the exogenous influences on the model.

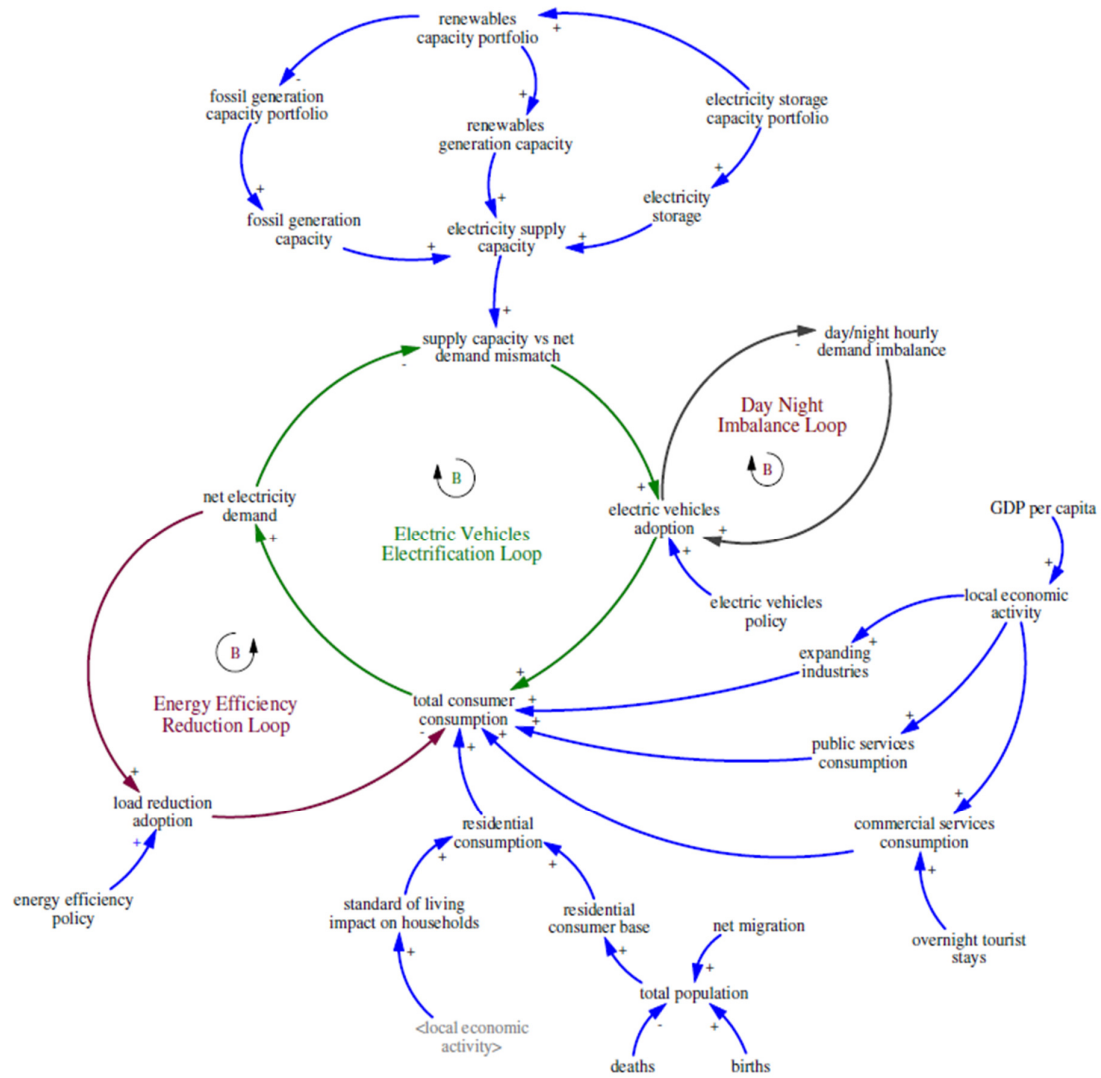


Figure 1: Mental model hypothesis of the key demand-driven components in the electricity system

Shown in Figure 1, the balancing effect, *EV electrification loop* (green loop) is central to the system. This loop is influenced exogenously by the electricity supply capacity. The electricity supply capacity variable is driven by the electricity storage, renewables and fossil generation capacities which are in turn driven by their respective portfolios. The portfolio values have a direct impact on the generation capacity since, in the absence of other drivers, the electricity system converges on this fraction of total installed capacity during the model simulation. For this study, the storage and renewables capacity portfolios are fixed as a fraction of total

capacity, as determined by the specific case study. Hence they are held constant throughout the simulation. The electricity storage is linked to the renewables capacity portfolio which in turn influences the fossil fuel generation capacity portfolio.

The point of interaction of the electricity supply capacity with *EV electrification loop* is the supply capacity vs. net demand mismatch. This mismatch is determined in the model as a value between 0 and 1. This variable is vital for checking that the system has the long-term supply to meet demand. For example, if the demand/supply capacity ratio is greater than 1 the supply is not sufficient to meet the demand, which is a worst case scenario for the system. The mismatch is reinforced by the electricity supply which, in turn, reinforces the EV adoption and the net electricity demand within the system. The net electricity demand, however, has a balancing effect back onto the supply capacity vs. net demand mismatch. The reinforcement of the supply capacity vs. net demand mismatch on the EV adoption is captured as a threshold influence. If the mismatch is higher than the threshold (set at 0.8) then the EV policy is not enforced to ensure that the supply is sufficient for the new demand. The exogenous EV policy also reinforces EV adoption. This EV policy is defined as a desired percentage of EVs from the total amount of light-duty vehicles within the island in 2015, which is the start time for EV policy within the island system. The desired value of 6%, equivalent to approximately 2000 electric vehicles, is used for the policy implementation in this study (Bothelo, 2015; Nunes, 2015). The policy-based EV adoption is implemented using the goal-seeking approach given in (Sterman, 2000). Non-policy based EV adoption was implemented using the (Bass, 1969) diffusion model. In addition, the EV adoption is influenced by the *day-night imbalance loop* (black loop) which balances the EV adoption variable. If the day/night hourly demand imbalance is high then the incentives to adopt EVs is much higher than usual. This increase in EVs, however, balances the day/night hourly demand imbalance, closing this balancing loop. Also shown is the *energy efficiency reduction loop* (purple loop) which captures the balancing

effect of the energy efficiency measures on the net electricity demand. Energy efficiency policy is applied to give the required load reduction adoption which is reinforced by the net electricity demand. This exogenous energy efficiency policy is implemented independently within the different sectors of the system.

The resulting net electricity demand is equivalent to the consumer consumption with energy efficiency measures applied to the system. This total consumer consumption is derived from the endogenous EV adoption and energy efficiency influences together with the residential, commercial, industrial, and public services consumer types tied to the exogenous (GDP influenced) local economic activity. In the case of the residential and commercial consumer types there are exogenous influences from the population and overnight tourist stays, respectively. Relevant historical data for these key variables are used within the model (EDA, 2016; European Commission, 2013; ISLE-PACT, 2012). The model captures the endogenous electricity demand changes across all island electricity consumer types given the scenarios are driven by electricity supply security and environmental concerns. Other exogenous factors used within the model are the renewables and energy-storage policy portfolios and the fossil capacity portfolio which reflects the percentage of capacity required by the specific supply technology to satisfy the demand. In addition, the seasonality effects on the capacity factor of the renewables generation were exogenous while external adoption of tourism, system profitability and differentiated renewables technology (here aggregated and assumed to be geothermal) are excluded from the model. The detailed parts of the model in Figure 1 were implemented using standard SD formulations and mechanisms in the Vensim software package (Ventana Systems, 2016).

3.2. Model Assumptions

One of the assumptions in the SD model is that capacity investments within a specific generation technology are the result of the respective exogenous policy requiring portfolio contributions from each type of generation technology. For example, investments for renewables capacity are driven by the renewables capacity portfolio. However, the aggregated total capacity investments needed to meet the long-term demand are based on the expected electricity demand trends. Therefore, the average monthly long-term demand is considered as a key performance indicator of the model. Additionally, the short-term daily profile load curves used for matching the tolerable amount of EVs that can be charged during the low-demand trough period of the historical load duration curves, are pre-processed and used as a proxy within the model. The difference between the peak and trough of the short-term daily profiles is the desired amount of EV electrification and is reflected well within the model. In the EV policy part of the model, EVs are assumed to be light-duty and charge once per day for approximately 8-10 hours (which, given the geographical constraints of the island, is a reasonable assumption). Furthermore, the projected demand growth rate for the island is not used explicitly nor are economic consumption elasticities considered, but the GDP forecast is used as a proxy for determining the yearly increases in the absolute consumption of each consumer type. Finally, it is assumed that there are no cost considerations for new capacity builds or CO₂ emissions in this model, and that tourism growth is a totally exogenous entity and any influence on the GDP of the island system is neglected.

One constraint on the SD model is that it gives the average consumption and not the true peak demands and troughs for the various consumer types within the system. Consequently, the model does not account for the short-term hourly balancing of the grid system, although it does

capture the demand supply gaps for filling the low demand periods. However, crucially the model gives key insights into the structure of the system and reflects all the important feedbacks that drive the system.

3.3. Model validation

To validate the SD model, a number of structural validity procedures are performed (Barlas, 1989; Qudrat-Ullah and Seong, 2010). The first involves integration error testing to check that different integration methods do not give divergent results. Additionally, further validation includes defining the boundary adequacy of the model by defining what is exogenous to the model (i.e., GDP) and what is endogenous (i.e., the average demand and installed renewables capacity) and separating these from what has been excluded from the model, such as investment costs. This gives the context and gives confidence for the correct usage of the model, namely understanding the long-term endogenous demand within the system. Key variables used like electricity prices and consumption data were verified with EDA and with global data sources (EDA, 2016; European Commission, 2013; Ilic et al., 2013; ISLE-PACT, 2012). It is important to stress the dimensional consistency and structural verification of the model are built into the modelling software (Sterman, 2000; Ventana Systems, 2016). The Vensim package gives an error and does not run accurately if the equations do not satisfy this level of consistency. Some extreme condition testing has also been completed, which has sensitivity to inclusion/exclusion of different policies and to low/high values of the initial GDP.

Finally, it has been checked that the new SD model emulates the real system accurately during the calibration period (2005-2016), by taking into consideration historical data, domain expertise from EDA and theoretical formulations. The calibration period is followed by the simulation period, which gives insights into the future of the system after all available historical data. Within this calibration period, the patterns of behaviours being exhibited by important

system variables should be mimicked by the model. For example, shown in Figure 2 is the plotted historical data of the monthly consumer demand from 2005 to mid-2016 (red curve), compared to the simulated average monthly demand (blue curve) over the same period.

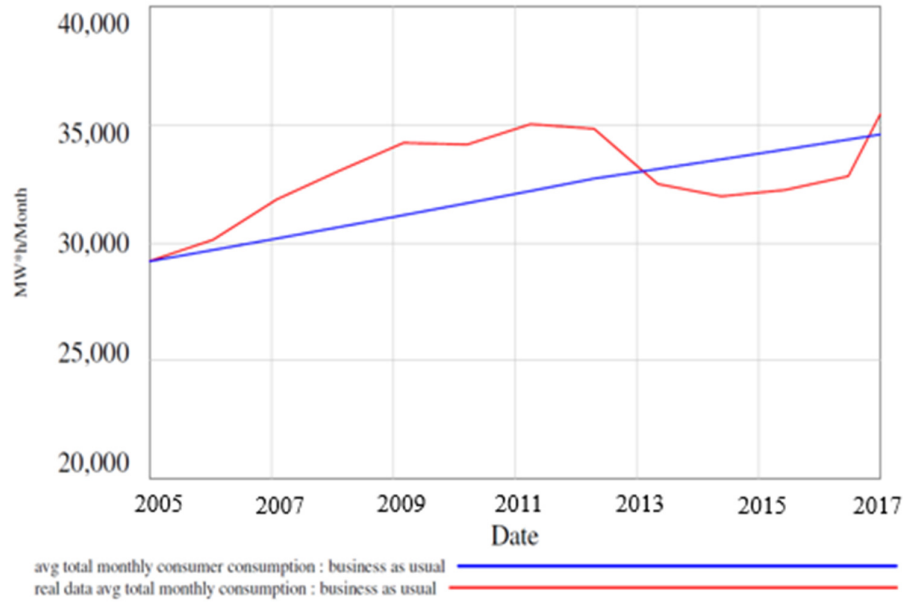


Figure 2: Fitness of base model output data to the real data

Visually, the simulated model output reflects the trend of historical data considering that the historical data are discrete monthly values whilst the model output is the average monthly value. However, a statistical measure of fit R^2 , (which measures the covariance) was used together with the Theil inequality statistics to characterise the source of error for analytical comparisons (Pierson and Sterman, 2013; Sterman, 2000). For the data series shown in Fig. 2, $R^2 = 5\%$ which indicates that the average monthly demand does not point-wise replicate the historical data. However, the new model is designed to analyse the long-term behaviour that results from short-term monthly consumption movements. The cyclic point-by-point historical data consist of slight divergences from the long-term average consumption trends.

These short-term monthly consumption divergences may be due to seasonality consumption effects not captured within the model. By using the Theil inequality statistics (Stermann, 2000), a method which decomposes the Mean Square Error into U^M (bias-unequal means of model and actual data), U^S (unequal variations) and U^C (unequal covariations), the source of error between the simulated and historical data series can be determined. For the Fig. 2 data series, Theil statistics found that U^M is 0.12, U^S is 0 and U^C is 0.88 which suggests the error is concentrated in the unequal covariations. This implies the model has the same mean and trends as the data but differs from the point-wise data., so the data fit compares favourably to other SD models (Pierson and Sterman, 2013), for example.

4. Policy scenarios for demand dynamics

To generate plausible scenarios to critically evaluate the evolution of the endogenous electricity demand, as mentioned in Section 1, three key system factors that influence energy-related policies are considered, namely: (i) energy efficiency; (ii) tourism growth; and (iii) electrification of the transport sector (light-duty EV). These were chosen based on the literature, (Bothelo, 2015; ISLE-PACT, 2012; Nunes, 2015) and because they are deemed to be potentially important drivers for the future of the evolving electricity system. In addition to these three scenarios, a baseline (business as usual) case has been included. The scenario considers the system in 2005 to mid-2016, together with the past and present policies and the current economic and social aspects. However, the existing renewables policy, which was enacted in mid-2008 to achieve approximately 75% renewable capacity by 2020, has been revised to 50%, based on the current rate of its installation (EDA, 2016). This value has been used for all scenarios.

The key features of the four test scenarios are:

4.1 Scenario 1: Business as usual

The island population is determined by the current birth and death rates along with the GDP growth rate, both being extrapolated from the 2005–2016 data. The current policy for an island-wide, energy efficiency target of 6% decrease in consumption over the next 10–15 years starting from 2012 is implemented. No EV policy or market influences are assumed aside from a normal increase in EV (based on the purchasing rate of new EVs in 2015). The growth rate in the number of overnight tourists stays is determined from the 2005–2016 data to be 0.14% (SREA, 2016), and extrapolated into the future.

4.2 Scenario 2: Tourism impact

This scenario examines the plausible impact of changing tourism on the demand of the electricity system. It uses the *Scenario 1* characteristics apart from the overnight tourist stays growth rates. For tourism growth rates, given from the historical data (SREA, 2016), two different cases are studied, namely, a reduction in the growth rate from 0.14% per month to 0.07% per month from 2016 until 2050 and an increase in the growth rate of 0.14% per month to 0.28% per month from 2016 until 2050. Furthermore, these two cases are of interest to EDA and the Regional Directorate for Energy of the Azores (Bothelo, 2015; Nunes, 2015). The scenario seeks to establish upper and lower bounds on the tourism impact upon the system. It is assumed that no new hotel construction is warranted due to the low existing occupancy rate on the island of 32% (ISLE-PACT, 2012; SREA, 2016), and the growth rate has only been doubled for this scenario.

4.3 Scenario 3: Energy efficiency measures

This scenario encapsulates *Scenario 1*, apart from variations in the energy efficiency policy. Two case studies are considered: namely, the doubling (to 12%) and tripling (to 18%) of the

original policy targets across the policy timeline of 10-15 years. This is a long-term energy efficiency target so in the SD simulation, the energy efficiency policy measures are discontinued after 15 years. It is also assumed that the energy efficiency measures are fully adopted by the consumers (so there are no adoption dynamics) since the extreme non-adoption will be reflected in the “business as usual” (*Scenario 1*) case.

4.4 Scenario 4: EV expansion

This scenario examines the possible influence of EV expansion. The baseline case is the purchasing rate of EV on the island in late 2015. It is also assumed that light-duty vehicles are the target for EV expansion. The baseline case is compared to three other policy cases: a market-based adoption policy for diffusion of technologies (Bass, 1969), a target of approximately 2000 EVs by 2020 (as suggested by EDA) (Bothelo, 2015), and a combination of the 2020 EV and the market-based adoption policies.

5. Results Discussion

5.1.Scenario-specific demand dynamics

5.1.1 Tourism impact

Figure 3 displays the influence of changing the growth rate of the number of overnight stays and the corresponding average monthly demand. The bottom half of Figure 3 displays the effects on hotel long-term demand trends, while the upper half shows the resultant effects on the system-wide long-term electricity demand trends. In both cases, the “business as usual” scenario, the black curve in the bottom half of the figure and the red curve in the top half of the figure, lies between the reduced and the increased overnight stays growth rates. However, the

demand is seen to be high within the hotel consumption portion from 2016 onwards but this is only evident by a very small change from 2040 onwards within the total system demand. This phenomenon occurs because the hotel sector commands a very small share of the consumption within the island system. Hence with a doubling or even tripling of the hotel consumption, there will not be visible effects in the shorter term.

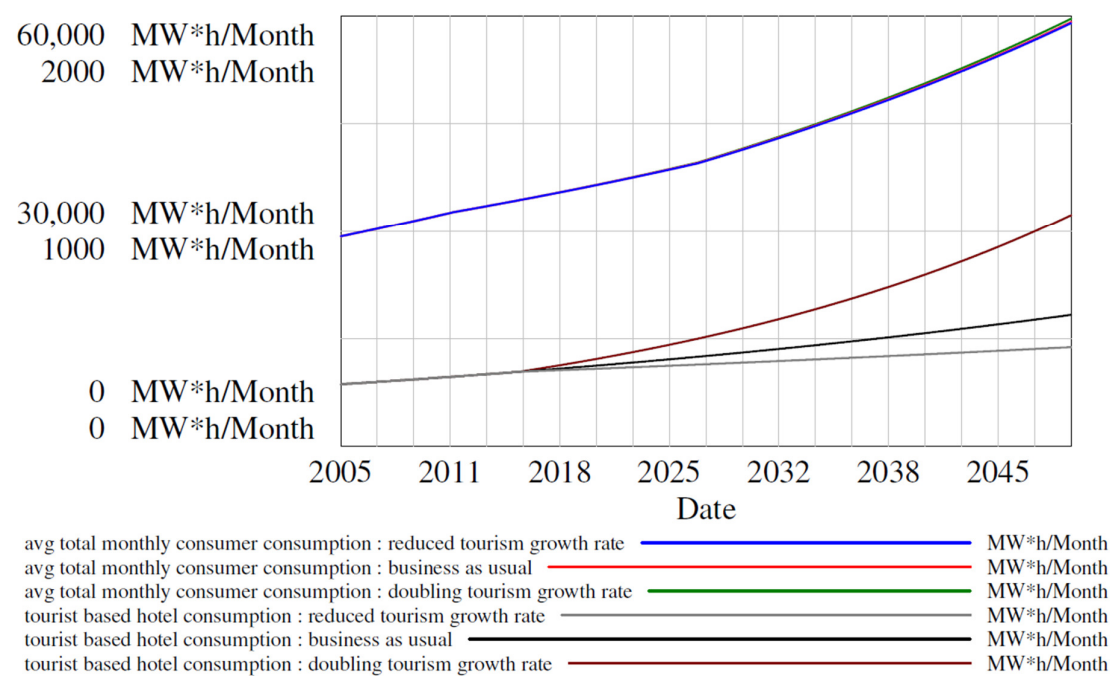


Figure 3: Impact of varying scenarios of tourism changes on the total monthly demand of the electricity system

A pragmatic conclusion from these results is that tourism on São Miguel has a low long-term electricity demand impact and that policies that either increase or decrease tourism do not significantly affect system-wide demand. However, it is evident that the consumer demand within the hotel sector will be increased by a significant amount in the case of increasing the overnight stays rate and decreased in the case of decreasing the overnight stays rate, compared to the “business as usual” scenario. It is important to stress that the tourism share of the total system consumption is initially very low, as the cause for the observations. An island system

that has a relatively large share of demand based on tourism will show more influential dynamics including a higher trajectory on the long-term demand.

5.1.2 Energy efficiency measures

Figure 4 shows the varying energy efficiency impacts on the whole system, for the long-term average monthly demand of electricity. The energy efficiency measures are considered for the aggregated system as a whole and not restricted to specific consumer types. Current energy efficiency policy of 6% demand reduction from 2012 for 15 years (proposed by EDA and the Regional Directorate of Energy) is reflected by a slight dip in the trend of the load curve (red curve) for the “business as usual” scenario shown in Figure 4. The effects on the long-term demand load of doubling and tripling (blue and green curves respectively) the required demand reductions over the same timelines show greater deviations from the initial trend of the load curve, with tripling the reductions having the largest effect.

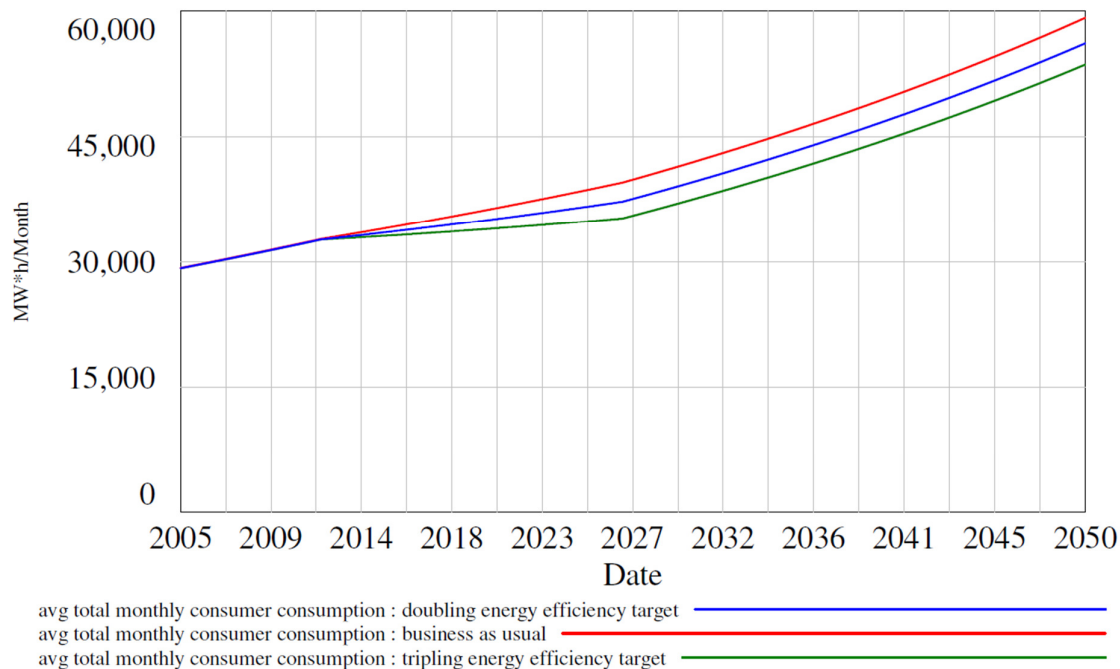


Figure 4: Impact of energy efficiency measures on the total monthly demand of the electricity system

The results reveal that energy efficiency measures can be applied as a blunt policy tool with high impact. Reductions in consumption in the long-term are guaranteed if efficiency measures are applied in the shorter term (10-15 years) with more aggressive targets being set. This means energy efficiency policies have a significant impact on the demand dynamics of the electricity system and can be applied as an additional safeguard for long-term energy security.

5.1.3 EV expansion

The introduction of EVs within island systems such as the Azores has been very slow and without any policy support (Nunes, 2015). This is contrary to the mainland Portugal where there are various incentives initiated to encourage their adoption. In 2016, São Miguel has a fleet of approximately 50 EVs. Given the current low uptake on the island and in the absence of other major changes, the “business as usual” scenario has been modelled revealing that there will be approximately 110 EVs on São Miguel by 2050, based on the 2015 purchasing rate.

EV expansion for the electrification of the transportation sector is integral to increasing the renewables capacity of the island system. Since the base case has a small number of EVs there is considerable potential for policies to drive their expansion. These include setting explicit target numbers or incentivising the market adoption of EV. The comparisons shown in Figure 5 provides insight into the resulting number of EVs with policies differing from the “business as usual” case (red curve). Figure 5 also shows (right-hand scale) the equivalent amounts of long-term monthly demand that will be added to the electricity network from these different policy scenarios. The number of EVs and their trajectory to 2050 shows greatly differing dynamics depending on the chosen policy. The blue line indicates the number of EV to 2050 following market-based expansion based on adoption diffusion. The hybrid policy (grey curve) of planning for a fixed amount of vehicles by 2020 and then supporting market adoption, yields the most impact on the penetration of EV.

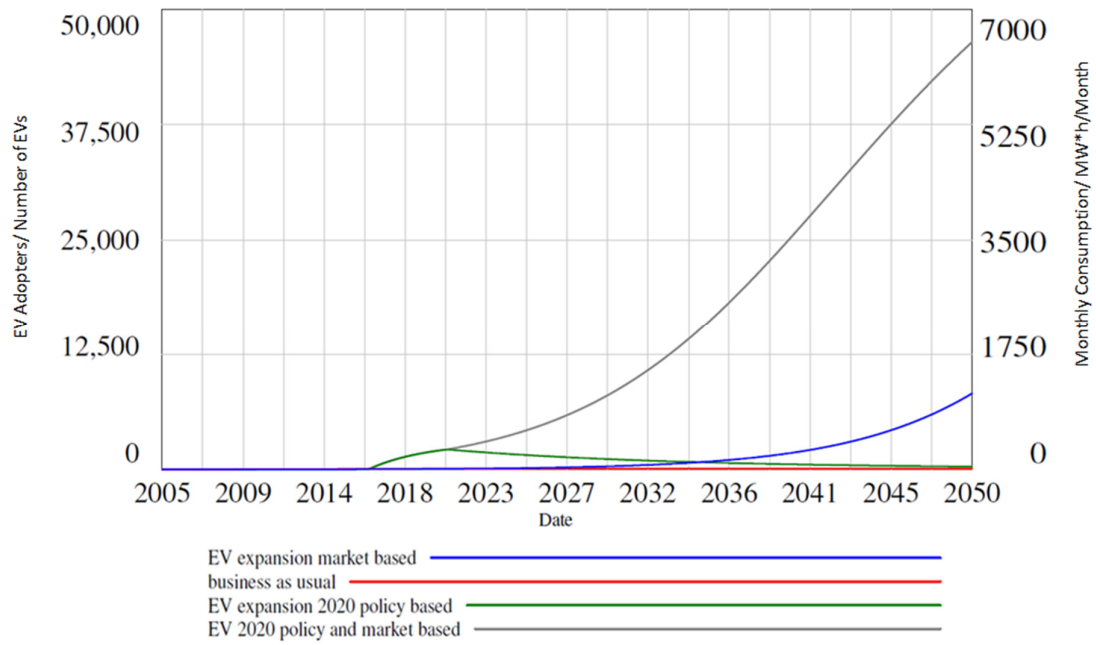


Figure 5: Model output for the number of EV adopters and monthly EV consumption under varying cases of EV expansion policies

Interestingly, the results reveal that a 2020 policy which has no on-going support to encourage the sustained use of EV (green curve) will lead to a gradual decline in EV numbers and EV-based electricity demand in the longer term. This is because after an EV has passed its lifetime it will be discarded. If the 2020 policy is no longer in force, then, as adopted EVs reach their end of life, they are no longer used within the system. This leads to a long-term decline in consumption caused by the removal of EVs. In contrast, with the hybrid case in which the 2020 policy target is used along with market adoption and leads to an exponential increase in the number of EVs and equivalent electricity demand.

Figure 6 shows the EV impact on the whole system, for the long-term average monthly demand of electricity. It reveals that the hybrid policy has the highest impact on long-term demand dynamics and that EV expansion can have a marginally small or high impact on the long-term demand dynamics and presents challenges for policymakers. As shown in (Bakker and Jacob

Trip, 2013; Green et al., 2014) government intervention can be useful to facilitate/lead EV adoption, however, policies must be carefully applied to avoid compromising security in meeting this demand. Conversely, the environmental benefits and advent of more renewables capacity, facilitated by high amounts of electrification of the transportation sector encourages EV expansions in the absence of policy targets or incentives (IEA, 2013).

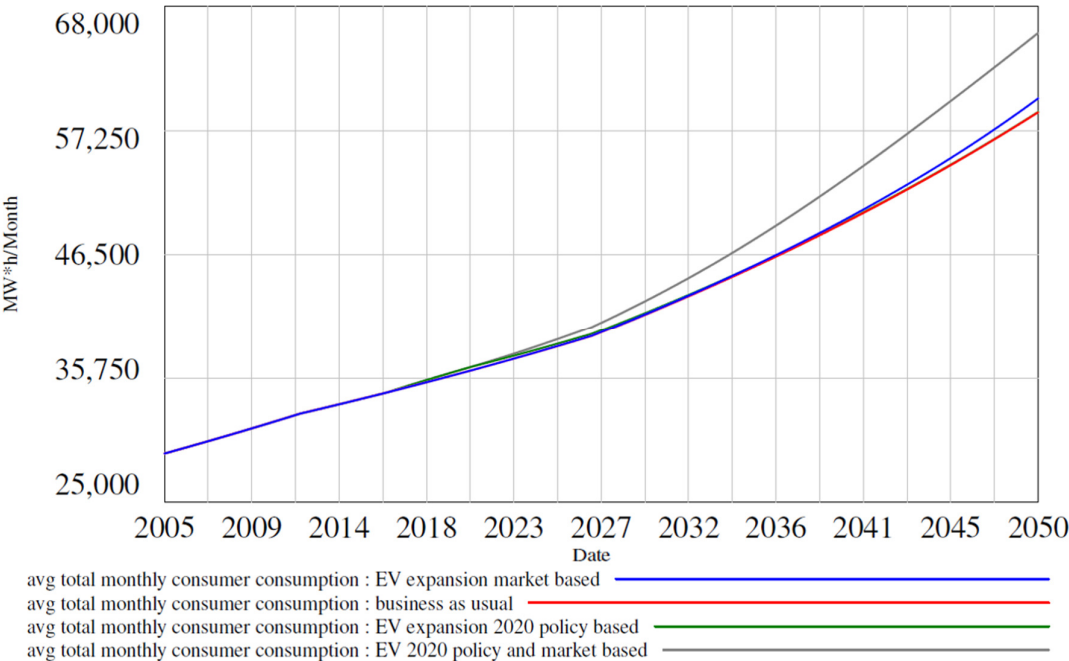


Figure 6: Impact of different EV expansion policies on the total monthly demand of the electricity system

This analysis reveals that EV expansion is potentially more interesting in terms of the long-term impact compared to both tourism growth and energy efficiency measures, though energy efficiency remains the most powerful for guiding the long-term demand dynamics. In addition, supply-side influenced demand such as energy efficiency will have a narrower range of impacts on the long-term demand compared to demand-side influenced factors such as EVs. The range of possible outlooks for the EVs on the long-term demand can vary from being negligible to being very large.

5.2. Long-term demand and supply confidence bounds

Figure 7 shows the confidence bounds on the long-term demand of the system as determined from a series of 200 Monte Carlo Marko Chain simulations randomly sampling the four scenarios detailed in Section 4. Key variables, their ranges, and related information sources are given in Appendix, Table A.1. The result shows that the demand can be tightly bounded with a 75% probability given the combinations of different policies for electrification, energy efficiency and tourism, implying that long-term demand dynamics driven by policy can provide a stable outlook for the system. However, careful considerations must be given to the policy choices since the 95% confidence bounds (blue regions) are upwardly skewed over a larger uncertainty range when compared to the mean (red line).

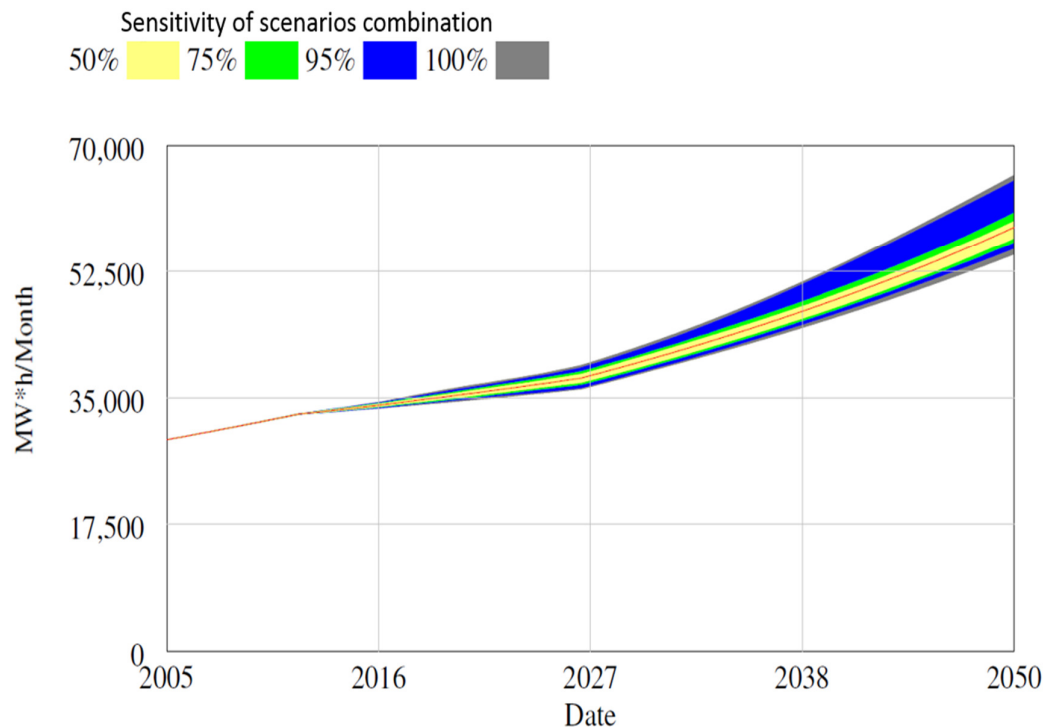


Figure 7: Total monthly demand sensitivity of the electricity system for the different policies from 2005 to 2050

Figure 8 displays the Monte Carlo simulation confidence bounds for the installed renewable capacity in MW. These bounds have been calculated from 200 runs of the combinations of the scenarios detailed in Section 4. The greater disparity that is evident in the 75% -100% confidence bounds is mainly driven by the renewable energy policies. The results reveal that the installed renewables pathway based on a 50% portfolio share is consistent with observations to 2016. However as the time-period extends, the scenario combinations driving the renewables policy introduces uncertainty. The lower confidence bound is guided by the energy efficiency measures whilst the upper part is bounded by the policies relating to the electrification of the transport sector. This implies that greater electrification will, in the long-term, lead to more renewable capacity within isolated island systems.

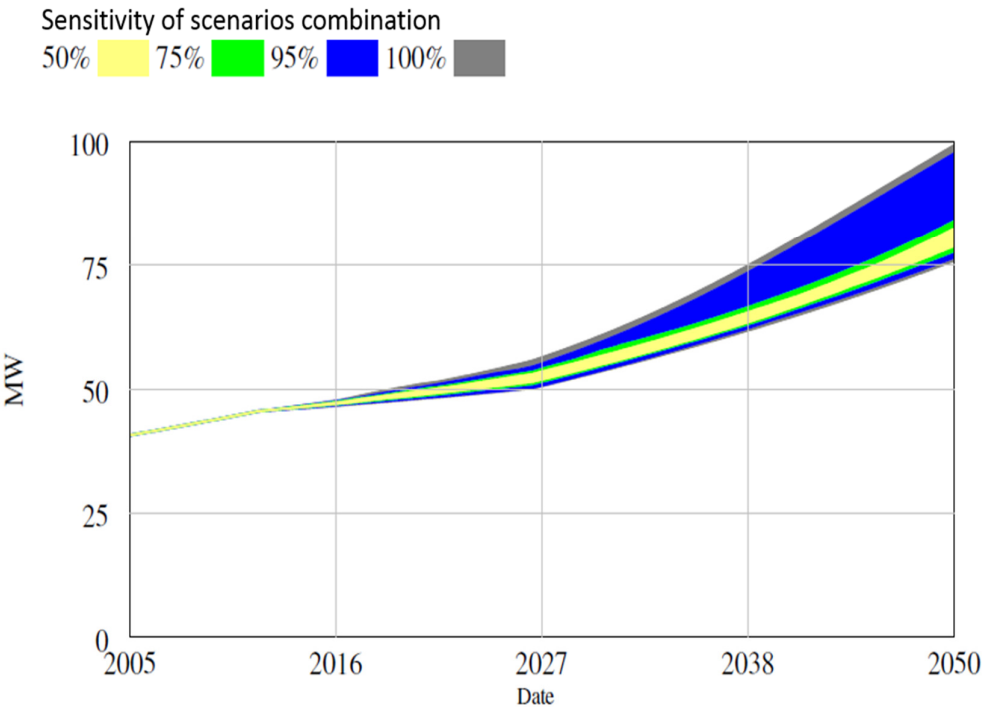


Figure 8: Sensitivity of the total installed renewable capacity of the electricity system for the different policies from 2005 to 2050

6. Conclusion and Policy Implications

The new SD model presented in this paper has analysed a series of policy scenarios which emphasise differing critical factors for the long-term endogenous demand dynamics and identify the most important and interesting factors for policymakers when considering their environmental and energy security objectives. By applying a series of pragmatic assumptions, the policies for electrification of the transportation sector, energy efficiency measures and increased tourism activity provide an insightful understanding of the demand dynamics of an island electricity system. Based on the model behaviour for these scenarios, it can be concluded that the long-term demand trajectory is significantly influenced by implementing successful energy efficiency measures. This is, however, a brute force solution for reducing the long-term monthly demand and can be a useful policy for safeguarding the energy security of the system. EV expansion is not as influential, although it can still provide medium-to-large stimuli to the long-term demand dynamics. This is demonstrated by the different demand projections for EV expansion by 2050. Longer-term demand is uncertain with both small and large changes feasible depending upon the way EV are adopted and related policies are pursued. If specific policy targets are withdrawn, once they have been achieved, then long-term demand will converge closer to the “business as usual” path. This shift is small compared to a hybrid policy involving the market effects, which is very large for such adoption of EVs. In such cases, the long-term demand dynamics can diverge from the “business as usual” scenario. To achieve higher levels of electrification, the chosen policy can be guided by the key stakeholder, by, for example, replacing company and government vehicles with EVs and actively promoting their benefits and encouraging the rest of the island to adopt EVs, a concept embraced by the Regional Directorate of Energy (Nunes, 2015).

Finally, for islands such as São Miguel policies relating to conventional tourism have a very low impact on the long-term monthly consumption trends, indicating that systems with a very small initial tourism economy need a substantial increase in tourism if this is to impact the long-term demand trends. The implemented tourism policies in this case study made little impression on the long-term trajectory of system demand, implying that isolated island systems with a low economic share of tourist activities are largely unaffected by energy-related policies which focus solely on tourism. Furthermore, for isolated island systems pursuing low-carbon objectives, it is the policy behaviour of the locals rather than externals (tourists) that will make the key impact on the future electricity system. This can, however, be different in smaller and less developed island systems than the one studied in this paper, but fundamentally what matters to any island system is knowing that its mechanisms are able to reduce the demand as a safeguard and eliminate the need for additional generating capacity. EV electrification policies are useful in reducing the environmental impacts of high CO₂ emissions; however, they have a lower impact on the long-term demand than successful energy efficiency measures. The model provides new clear insights into the most important and influential policies for the endogenous demand dynamics from the key socio-techno-economic aspects typical to the structure of island electricity systems. This new SD model provides a novel approach to identifying the most influential and efficient policies by understanding the structure of the system useful for the long-term electricity consumption of island systems. The approach gives sustainability guidelines and policy directions for prospective energy solutions. Demand policy implications are important in making informed decisions and being aware of which policies are the priority where the focus for energy security and environmental issues must be directed. This is essential for understanding how the policies impact on the overall long-term endogenous demand.

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