Open Research Online

The Open University's repository of research publications
and other research outputs

Low Carbon Futures: confronting electricity challenges on island systems

Journal Item

How to cite:

Matthew, George; Nuttall, William; Mestel, Benjamin and Dooley, Laurence (2019). Low Carbon Futures: confronting electricity challenges on island systems. Technological Forecasting and Social Change, 147 pp. 36–50.

For guidance on citations see FAQs.

© 2019 Elsevier

https://creativecommons.org/licenses/by-nc-nd/4.0/

Version: Accepted Manuscript

Link(s) to article on publisher's website:
http://dx.doi.org/doi:10.1016/j.techfore.2019.06.014

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data policy on reuse of materials please consult the policies page.

oro.open.ac.uk

Low Carbon Futures: Confronting Electricity Challenges on Island Systems

Abstract

This paper considers the range of possible long-term futures for an electrically isolated island power system. Emphasis is given to generation investment decisions supportive of low-carbon renewable generation. Ranges of policy interventions are considered for the electrically isolated case study island of São Miguel in the Azores islands in the North Atlantic Ocean. The whole systems methodological approach of System Dynamics is used to bring together key sub-systems relating to~~, for example,~~ generation adequacy, renewable generation investments and demand-side aspects. In this way, a comprehensive understanding is established with high levels of endogeneity. The model is used to investigate a range of policy scenarios associated with renewable energy growth, electric-vehicle uptake and electricity storage. It is found that policy is most effective when all aspects are addressed simultaneously and in a co-ordinated manner and that policy favouring renewable generation alone is not sufficient to achieve the highest possible penetration of renewables. Finally, the robustness of the observations is addressed via Monte-Carlo based sensitivity testing.

Keywords

Low-Carbon Futures; Island Electricity Systems; System Dynamics; Electricity Transitions; Sustainable Energy

1. Sustainable Low-carbon Electricity Systems on Islands

The pursuit of low-carbon renewable sources addresses the challenges of high energy prices, energy security relating to the import dependency of fossil fuels, and CO_2 emissions (European Commission, 2016; Foxon, 2013; IRENA, 2013; UNFCCC, 2016; Weisser, 2004). Renewables are improving access to modern energy services and can enhance the sustainability and resilience of electricity systems (UNF, 2013).

Consequently, incentives are being implemented worldwide to improve electricity systems through environmentally friendly sources, while upholding reliable energy supplies. The use of low-carbon energy sources, energy efficiency and other resources (UNF, 2013; Islands Energy Program, 2016) provides electricity systems with the requisite tools for sustainable energy provision. Such systems are now moving to higher levels of renewable energy generation with new technologies facilitating these transitions. Emerging challenges will further shape the low-carbon outcomes and policies. It is therefore important to understand the ways in which policy can influence the large variety of future trajectories for electricity systems.

In our work, we apply these considerations to the particular context of electrically isolated island systems, in particular the Azorean island of São Miguel (Matthew et al., 2017, 2016).

1.1 Evolving Low-carbon Electricity Systems - Socio-techno-economic factors

An objective for policy makers is to transition current electricity systems to satisfy increasing populations and their desire for uninterrupted power supply (IEA, 2016), coupled with fulfilling global climate change targets (European Commission, 2016) and tackling an overreliance on fossil fuels (European Commission, 2016). Future electricity systems should be diverse, dynamic and evolving low-carbon integrated systems. According to MIT (2011), while the majority of current electricity systems are not yet broken, the emerging challenges from the energy transition could substantially degrade system reliability and efficiency.

Island electricity systems are already experiencing an evolution from traditional centralised fossil-based generation to a predominately decentralised low-carbon architecture (Islands Energy Program, 2016; Vallvé, 2013). New types of low-carbon and smarter systems enabled by pervasive ICT will emerge with bidirectional communications and power exchange between suppliers and consumers (Bompard et al., 2012). These systems are not limited to an already diverse set of dynamic, distributed energy suppliers, but should also connect smart users (i.e., those who are responsive, energy efficient, and variable) to sustainable energy sources. Many challenges and opportunities arise from the development of these systems and services. There is evidence that such changes, mediated by public policies and a variety of technological, social and economic changes, can alter both the demand and supply of electricity (MIT, 2011). The implementation of such changes involves both operational and architectural factors. There is a need for newer policies and renewed investment strategies for generating, delivering, storing, and consuming electricity. If regulatory policies and the technologies employed in the electricity system do not adapt, it will be difficult to maintain acceptable reliability and sustainability (MIT, 2011).

Traditional fossil-based electricity systems are imbued with numerous multi-level interactions (Chappin, 2011; Geels and Schot, 2007). The accompanying complex dynamics not only involve the technical and physical aspects but also various socio-economic systems interacting with them (Chappin, 2011; Geels, 2002). Future low-carbon electricity systems will be more complex than fossil-based electricity systems (Bompard et al., 2012; Foxon, 2011) due to the added physical, social and economic inter-relationships (Bompard et al., 2012; Chappin, 2011). Some of these interactions feed back into energy security concerns of low-carbon transitioning systems so stakeholders such as governments and energy suppliers must monitor them within the extended system, if the maximum long-term benefits are to be obtained. There is also a need to adapt behaviour to ensure that an evolution of low-carbon electricity system design and implementation goals are achieved. All these changes occur within the broader political and cultural context shaping policies and behaviours.

Energy policy is frequently framed as an “energy trilemma” of economic affordability, environmental concerns and security of supply (Nuttall, 2013; World Energy Council, 2016). These factors readily apply to island systems albeit sometimes in more heavily constrained ways.

In line with the scope of this special issue, the research presented here considers various types of public policy, together with initiatives and processes associated with the successful promotion of innovation. The focus of this paper is on economic development within the context of a small remote ocean island in the Azores archipelago. This special issue is titled *Global Shifts in Technological Power*, so cognisance is made of the leading role that relatively small, isolated communities can play in facilitating such global shifts. This is especially manifest in energy systems development in the Azores, where the islands have become the testbed for trialling pioneering research and innovation into energy transition. The novel work presented in this paper investigates the long-term investments and policy progress in the areas of energy, climate change and clean industries, which allied with water and food, comprise a key sub-theme for this special issue.

1.2 An Exemplar Isolated Electricity System

The work here focuses on one particular isolated island territory, São Miguel in the Azores. The rationale for choosing this territory is:

- It is part of Portugal, the European Union, and is economically developed.
- It is of sufficient size and complexity to emulate the attributes of larger systems, while not having electrical connections to any other island or to the mainland.
- While the island has some political autonomy, electricity tariffs are not set locally but are determined administratively in Lisbon, so the electricity system on the island is not economically isolated (EDA, 2008).

With an estimated population of 138K and a Gross Value Added of 1.96 billion euros in 2016 (SREA, 2018), São Miguel has a growing tourist economy and traditional sectors of fishing and farming. The main electricity utility in São Miguel, Electricidade dos Açores (EDA), is a fully regulated utility alongside a few independent power producers (less than 2% of total production) (EDA, 2016). In 2016, São Miguel had an annual electricity production mix comprising 53% fossil fuel, 36% geothermal, 6% hydroelectric (principally run-of-river) and 5% wind, and a total generation (in 2016) of 424 GWh (Franco et al., 2017). Capacity reserve margins are above 30%, which is required to maintain security of supply, leaving a significant amount of generation capacity unused for much of the year. Indeed, a significant amount of night-time wind generation in the winter months has to be curtailed, which is a motivation for the development of energy storage. While the high level of geothermal generation makes São Miguel different from other island systems, the dependence on fossil fuels is highly typical of isolated islands, so that São Miguel is well suited as an exemplar system of low-carbon future challenges. Note that the scenarios detailed in Section 3 have been developed in discussions with EDA and therefore relate to challenges and policy options directly applicable to São Miguel, as well as to other island systems.

The historical dependence of São Miguel on imported fossil fuels is illustrated in in Figure 1.

The figure shows the increasing use of fossil fuels for electricity production in the years to 2006, followed by a gradual decrease from 2006 – 2018. This decrease may be attributed to the implementation of various renewable energy policies and objectives which are referred to in this paper.

Indeed, the Azores islands in the North Atlantic Ocean have been the focus of much international interest for energy and environment-related technology and policy research (Baptista et al., 2009; Ilic et al., 2013; Parness, 2011; Pina et al., 2012; Silva, 2013). This research has provided a foundation for a series of studies conducted by our group in recent years that has added a System Dynamics (SD) perspective to the growing body of knowledge (Matthew et al., 2017, 2016, 2015, 2014). This current paper represents a culmination of several previously presented strands of insight emerging from the SD approach. As such, the intention here is to achieve a more holistic level of understanding and to assess the overall system behaviours and the sensitivity of the system to various drivers, thereby achieving a more comprehensive depth of insight. The journey to this model has involved the development of several smaller models of simpler scope (as discussed in (Matthew et al., 2017, 2016, 2015)), so this more holistic model is termed the "synthesis model".

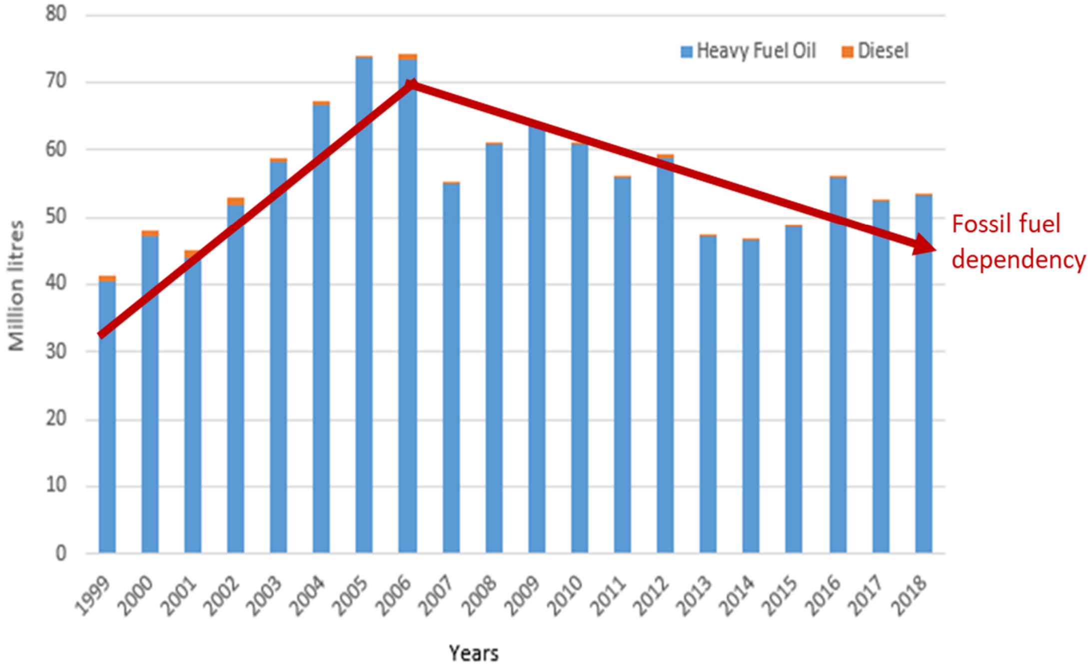

Figure 1 Diagram showing the quantity of fossil fuels (heavy fuel oil and diesel) used for electricity production in São Miguel from 1999 to 2018

The organisation of this paper is as follows. In Section 2, the System Dynamics modelling methodology is introduced and applied to model the low-carbon transition. A detailed discussion of the model is followed in Section 3 by a description of the three scenarios studied within this paper. The results and discussions are given in Section 4, followed by a concluding Section 5.

2. Modelling the Low Carbon Transition

SD is an established technique for analysing systems with complex dynamics through robust simulation guided by model diagrams that incorporate complicated interactions via a series of stocks and flows and feedback loops. Devised by Forrester (1961) as a tool for Operational Research, it has found widespread application in policy analysis and scenario planning. Starting from a conceptual model of the system, this so-called 'mental model' is developed, refined and simulated, typically within a comprehensive Integrated Development Environment (IDE), such as Vensim (Ventana Systems, 2018). For both an introductory textbook and a reference manual on System Dynamics, see (Sterman, 2000).

The SD application to a low-carbon transition in an island system involves an in-depth analysis of the growth of renewable generation taking into account demographic, economic, investment and policy drivers. In particular, the SD model is used to study the effect of three scenarios: *energy efficiency measures, Electric Vehicle (EV) expansion* and *renewables policies*, as described in Section 3 below.

The associated mental model feedback loop diagram is shown in Figure 2. It presents the key policy and investment feedback relationships that exist for the evolution and challenges encountered by an isolated small-island electricity system. The developed model will be shown later in Figure 3. The key causal relationships in Figure 2 are the four loops, two balancing (negative feedback) and two reinforcing (positive feedback), all interacting at the long-term low-carbon based capacity mix and the demand/capacity ratio variables. The main aspects captured by this model are the pursuit of low-carbon technologies aided by environmentally driven policies, and the interplay arising from the long-term electricity demand and the affordability of the various electricity-generation technologies.

2.1 Model Structure

Figure 2 has many interactions which determine the key endogenous variables of the model and which are now described in detail. These endogenous variables include: net CO_2 emissions, net electricity demand and expected revenues per MW of installed capacity. The key exogenous variables of the model are: the capacity utilisation, GDP changes, low-carbon policy targets and population changes. The various exogenous variables used were verified with EDA and with relevant global data sources (EDA, 2016; European Commission, 2013; Ilic et al., 2013; IRENA, 2014; Isle-pact, 2012).

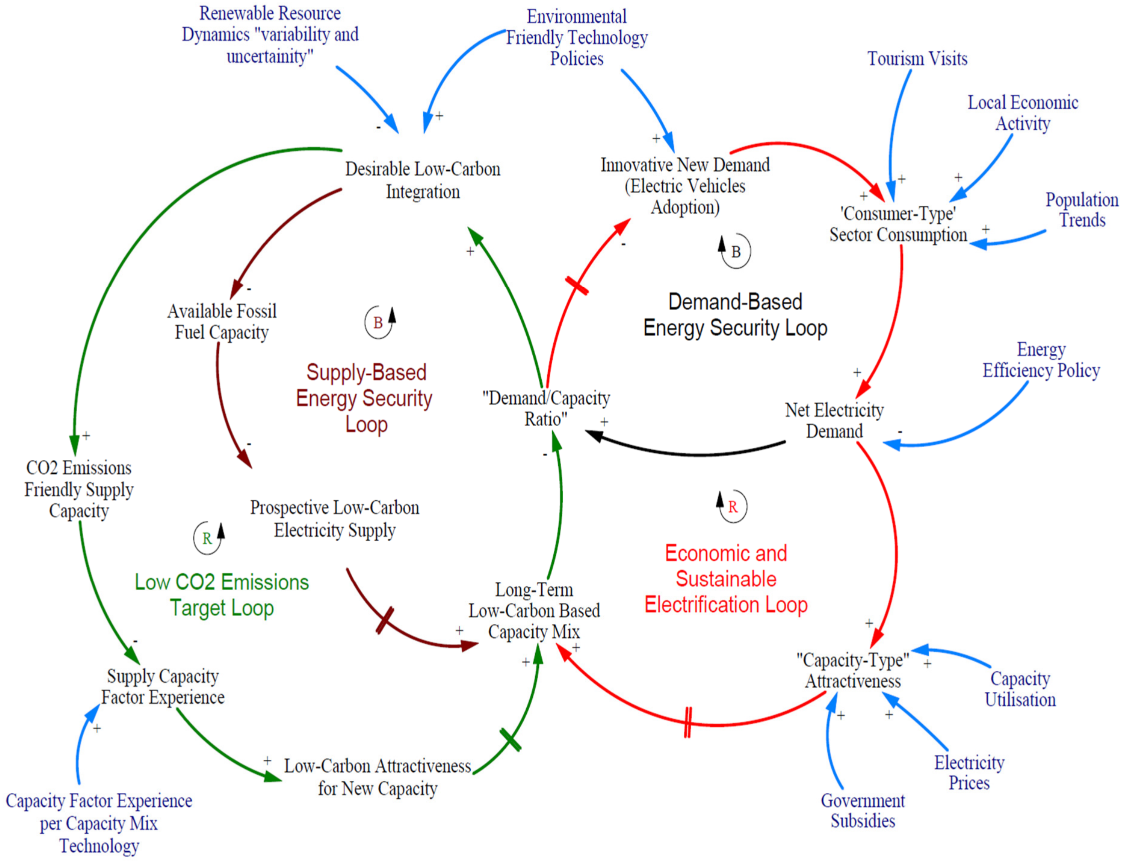

Figure 2 Mental model feedback diagram of the isolated island electricity system. The influence of exogenous variables is shown in blue.

As shown in Figure 2, three of the four loops, as the drivers to the underlying system structure, converge at the long-term low-carbon based capacity mix variable. A remaining loop interacts with the demand/capacity ratio variable. These loops represents the key causal relationships that exist within an isolated electricity system pursuing low-carbon futures. The demand-based energy security loop (red and black) captures the demand-side dynamics of the model, including the endogenous effects of a low-carbon policy. This loop includes the adoption of electric vehicles and energy efficiency mechanisms, and is reproduced from the endogenous demand sub-model in (Matthew et al., 2017). It details a loop that has a balancing effect on the demand/capacity ratio.

That ratio is useful for ensuring that there is sufficient electricity supply to meet the demand. If the demand/capacity ratio is high, then the level of innovative new electricity demand (e.g. electric vehicles adoption) is lower than it otherwise would be. We note that in every such case of innovative new demand there is a delay associated with the growth of this demand. The lowering of the innovative new demand as described (and as seen in our model via electric vehicle adoption) is reinforced via ‘consumer-type’ electricity consumption. The lower than normal effect described above is reinforced by the net electricity demand variable. This effect is then reinforced in the demand/capacity ratio variable. In this way, we complete the demand-based energy security balancing loop of Figure 2.

The three other loops interacting at the long-term low-carbon based capacity mix variable of Figure 2 reflect the key supply-side dynamics of the system. The outer low-CO_2 emissions target loop (green) is a reinforcing loop centred on the environmentally motivated drive for lower CO_2 emissions. If the demand/capacity ratio is high then the desirable low-carbon integration variable is higher than what it would otherwise be. Also interacting here are the exogenous effects of the renewable resource dynamics and environmentally friendly technology policies. The desirable low-carbon integration variable reinforces the higher-than-normal effect on the CO_2-emissions friendly supply capacity which then balances the supply capacity factor. Most low-carbon sources have relatively low capacity factors. The consequence in the model is that the supply capacity factor is lower than it otherwise would be. This decrease in supply capacity-factor is then reinforced onto the low-carbon attractiveness for new capacity which, in turn, reinforces the decrease of the long-term low-carbon based capacity mix. For the completion of the loop, the long-term low-carbon-based capacity mix variable has a balancing effect on the demand/capacity ratio. This variable is now higher than it normally would be and closes the reinforcing low CO_2 emissions target loop.

The inner supply-based energy security loop (brown and green) is also consistent with the environmentally motivated drive for lower CO_2 emissions. This loop, however, captures the fossil-fuel aspects of this part of the system so, as discussed above, if the demand/capacity ratio is high, then the desirable low-carbon integration variable is also higher than it would otherwise be. This increase, however, has a balancing effect on the available fossil fuel capacity variable. The resulting lowering effect on this variable has a balancing effect on the prospective low-carbon electricity supply variable causing it to increase. This increase, with a time delay, has a reinforcing effect on the long-term low-carbon based capacity mix variable causing it to be higher than it would normally be. As shown above, the completion of this loop involves the long-term low-carbon based capacity mix variable having a balancing effect on the demand/capacity ratio variable. If the supply-based energy security loop were acting on its own, then, due to the balancing effect of the loop, the demand/capacity ratio variable would now be lower than it otherwise would be. Additionally, factors relating to the intermittency of the different disaggregated renewable sources are included within the low-CO_2-emissions target loop and the supply-based energy-security loop.

In real world-policy making, the definition of term ‘energy security’ varies widely depending on context, with a multi-faceted approach often being taken. For example, the International Energy Agency (2019) defines energy security in economic terms as being:

> *“….the uninterrupted availability of energy sources at an affordable price. Energy security has many aspects: long-term energy security mainly deals with timely investments to supply energy in line with economic developments and environmental needs. On the other hand, short-term energy security focuses on the ability of the energy system to react promptly to sudden changes in the supply-demand balance”*

In contrast, other organisations weight the benefits of self-sufficiency and energy-independence like the Energy Security strategy of the European Union (European Commission, 2019) and assorted policies of key regulatory bodies in the United States of America, e.g. , United States Environmental Protection Agency (2019).

This paper deliberately adopts a pragmatic definition of energy security in that it represents a paradigm which is energy self-sufficient and either eliminates or has very low dependency on imported fossil fuels.

Not only are we working with this constrained definition of energy security based on low (fossil fuel) import dependency, we also do not focus equally on the whole energy policy trilemma, but instead put the focus on the nexus between the environmental and energy security (fossil fuel dependency) concerns of the island system. As such, we carefully ignore the economic and affordability aspects as the motivation for this research into modelling São Miguel in the Azores, was partly to allow such an approximation to be made without risking divergence from the real-world experience. As described in Section 1.2, Azorean energy economics is not local and endogenous. The island is not economically isolated (for energy pricing) from Portugal and prices are not determined via liquid local markets. This paper provides an insightful approach for mitigating the emerging policy and investment challenges and behaviour issues of low-carbon-transitioning island systems. Issues include sustaining the uptake and increasing the amounts of renewables, ensuring energy security (fossil fuel import independence), and understanding useful strategies that can improve investment decision-making for the electricity generation capacity mix. Critical policy recommendations allied with long-term investment observations, are influenced by these environmental and energy security concerns, have the potential to be revealed.

Figure 2 includes an economic and sustainable electrification loop (red and green) which captures the key long-term economic aspects of the system driving the low-carbon based capacity mix variable and, in turn, impacting on the demand/capacity ratio. This is a reinforcing loop and a similar starting point as the demand-based energy-security loop is assumed. If the demand/capacity ratio is low, then the delayed innovative new demand (i.e., electric vehicles adoption) is raised. This raised effect on the new innovative electricity demand then reinforces the ‘consumer-type’ sector consumption, which, in turn, reinforces the net electricity demand. Hence the net electricity demand is itself increased. This increase has a reinforcing effect on the ‘capacity-type’ attractiveness causing it also to be raised. Other exogenous variables key to the long-term economic aspects of the system also interact with the ‘capacity-type’ attractiveness. The capacity utilisation, electricity prices, and government subsidies have reinforcing effects on the ‘capacity-type’ attractiveness variable. The ‘capacity-type’ attractiveness variable then, with a delay, has a reinforcing effect on the long-term low-carbon-based capacity mix causing it to be raised. The completion of this loop, in a similar way to the low-CO_2-emissions target loop and the supply-based energy-security loop, involves the long-term low-carbon based capacity mix variable having a balancing effect on the demand/capacity ratio variable. Hence, if this loop were acting on its own, the demand/capacity ratio variable would be raised.

The four highlighted loops comprise the key components of the model structure, which captures the principal environmental and electricity security concerns of an isolated island system. The mental model is then used to formulate a full SD model, which is then applied to the exemplar island, viz., São Miguel in the Azores.

2.2 Model Formulation

The model in Figure 2 was implemented using the Vensim software package (Ventana Systems, 2018). The main mappings of the key stocks and flows and exogenous factors for this model are shown in Figure 2. For the analysis in this paper, the model is simulated on a monthly time-step over a 45-year time horizon 2005 - 2050, with the calibration period being between 2005 and 2015.

This means it is assumed that 2015 is the current year, and the modelling commences ten years earlier in 2005, so giving a ten-year time frame of data for both model calibration and validation. Moreover, by commencing the model in 2005 it means publically available datasets are applied to authenticate and refine key model parameters and relationships. This is advantageous because official datasets take a long time to be published due to assorted acquisition and publication practicalities and ensuring the data is neither commercially sensitive nor at risk of revealing customers' private information.

Rigorous validation steps are taken, as described in Section 4.1, to ensure the robustness of the model for studying the low-carbon energy transitioning and electricity challenges within isolated island systems.

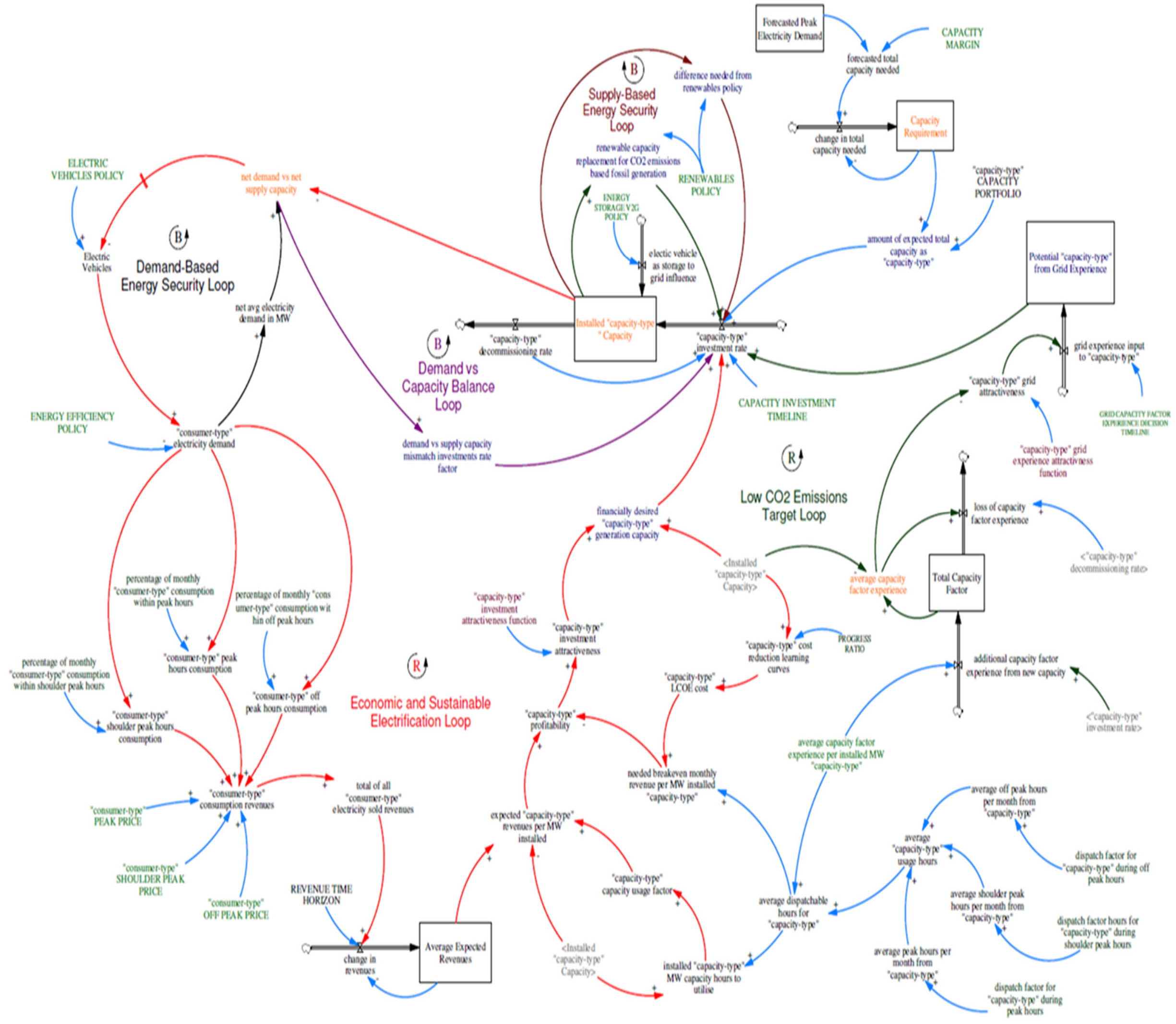

Figure 3 Stock and flow diagram of the isolated island electricity system. The structure presented here has some simplification from the full model.

In particular, during the calibration period, the patterns of behaviour of important simulated system variables (e.g., “installed fossil generation capacity”, “installed renewables aggregated capacity” and “installed energy storage capacity”) are required to follow the same trends as the real system data. Calibration is discussed more in Section 4. Other validation steps and detailed model formulations are described in (Matthew, 2017). While the approach developed here has been demonstrated on a system inspired by the case of São Miguel, it can be applied to other island systems. Any Island system that has a low-carbon agenda and is electrically isolated can be represented using the modelling platform developed for this research.

3. Scenarios

The three specific scenarios of potential importance discussed in this paper, together with the baseline (business as usual (BAU)) scenario, are derived from the literature (Botelho, 2015; European Commission, 2013; Isle-pact, 2012; Nunes, 2015). The specific scenarios are *energy efficiency measures, Electric Vehicle (EV) expansion* and *renewables policies*. These scenarios are hypothesised to be potentially interesting drivers for the future of the evolving electricity system that can give insights into the electricity system challenges for an isolated island system. One further putative scenario (tourism growth) was also considered, but found to have little overall impact within the assumptions adopted (Matthew et al., 2017). It will not be discussed further here.

In our SD modelling a scenario is determined via a set of values for exogenous parameters and the targets of specific policies (considered as a policy or influence-based effect in which one aspect is given dominance or particularly emphasised in some way). The model scenarios are simulated as individual simulation runs. By exploring the synthesis model through such scenarios it becomes possible to reveal key aspects of the potential for electricity futures on the island of São Miguel. The underlying model structure in each case is unchanged. The individual scenarios are now described.

Scenario 1: Business as usual (BAU)

This extrapolates the current trend of key factors and policies within the island system. The scenario uses system data from 2005 to 2015, together with the past and present policies and the prevailing economic and social conditions. Two important factors are the island population, which is determined by the current birth and death rates, and the Gross Domestic Product (GDP) per capita; both being extrapolated up to 2050 from the 2005-2015 historical data. The existing policy for energy efficiency: a target of 6% decrease in consumption across all consumer-type sectors 2012-2027 is implemented. The renewable policy, which was enacted in mid-2008 to achieve approximately 75% renewable generation by 2020, is replaced by a more modest 45% renewable installation. This adjustment of the policy is made to reflect rates of actual installation in 2015 (EDA, 2016). In addition, a medium-term goal of a 30% reduction in CO_2 emissions by 2020 is implemented within this scenario. There is also a 12 MW goal for a small reservoir energy storage project to begin in 2018, considered as a policy objective for the system (Botelho, 2015). (This project was confirmed in early 2019 to be delayed but is still illustrated within the paper for gauging its impacts.) There are no special EV policies or pronounced market influences beyond the prevailing increase in EVs (based on the purchasing rate of about 4 new EVs per year in 2015) which currently results in approximately 50 vehicles in 2015. For this scenario, the growth rate in the number of overnight tourist stays is determined from the 2005-2016 historical data to be 0.14% (SREA, 2018), starting with an initial value of 96,000 in January 2005 and extrapolated into the future. Using these as key inputs, the long-term trends and impacts within the system are simulated.

Scenario 2: Energy efficiency

This is the same as Scenario 1 except variations in the energy efficiency policy as described in Scenario 1 with two case studies considered: namely, the doubling (to 12%) and tripling (to 18%) of the original policy targets across the policy timeline of 15 years. The energy efficiency policy measures are discontinued after 15 years (Botelho, 2015; Nunes, 2015) while longer timelines are considered for the sensitivity analysis. It is also assumed that the energy efficiency measures are fully adopted by the consumers (no adoption dynamics for this model). However, the extreme case for non-adoption is reflected in the BAU case.

Scenario 3: EV expansion

This scenario examines the possible influence of EV expansion. It corresponds to Scenario 1 apart from the EV expansion. It is assumed that light-duty vehicles are the target for EV expansion, with a market-based adoption policy for diffusion of technologies (Bass, 1969), a target of approximately 2500 EVs by 2020 (Botelho, 2015), and a combination of the 2020 EV and market-based adoption policies.

Scenario 4: Renewables policies

This scenario features two case studies of renewable policies based around Scenario 1. A target of 30% reduction in CO_2 emissions and 45% installed renewable capacity within the system by 2050 is examined. In addition, a more aggressive 50% reduction in CO_2 emissions with 75% installed renewable capacity within the system by 2030 is also considered.

4. Results and Discussion

4.1 Model Calibration and Validation

Figure 3 shows the simulated base model output data compared with the historical data of the corresponding real system variables during the calibration period. There is no installed energy storage capacity within the system over this period as reflected in Figure 4.

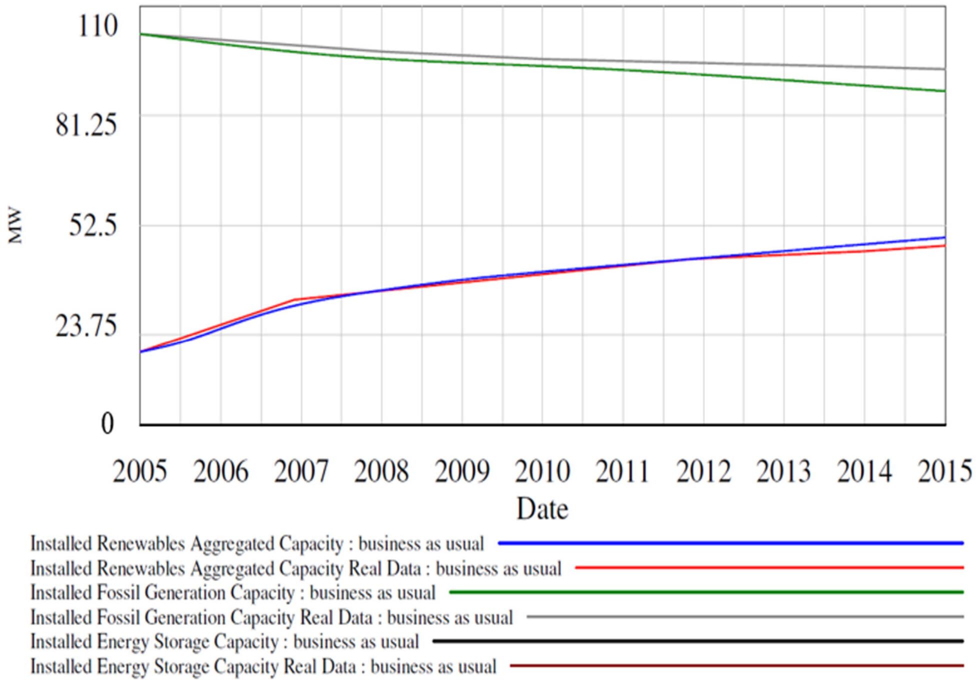

Figure 4 Comparison of base model output data and real data for the synthesis model during the calibration period 2005 - 2015, showing good agreement for the Installed Renewables Aggregated Capacity but some divergence for the Installed Fossil Generation Capacity. The Installed Energy Storage Capacity is zero during the calibration period.

Comprehensive statistical methods have been used to aid model calibration. A statistical measure of fit, R^2, and Theil inequality statistics (Sterman, 2000, Chapter 21) have been used to characterize the sources of error within the analytical comparisons of both the simulated and historical data. After refinements to the model formulations, and with further simulations of the base model, the resulting statistical values of some of the important variables are reported in Table 1.

Table 1 Model fits of historical data to some important variables [In this table "avg" refers to the mean]

Variable Name	**R^2**	**MAE/M**	**U^m**	**U^s**	**U^c**
avg total monthly consumer consumption	28.08%	0.0492	0.10	0.00	0.90
avg commercial services monthly consumption	69.66%	0.0870	0.14	0.02	0.84
avg residential household monthly consumption	24.82%	0.0395	0.06	0.04	0.90
avg industrial business monthly consumption	25.08%	0.0461	0.10	0.00	0.90
avg public services monthly consumption	26.70%	0.0263	0.27	0.54	0.19
Installed Fossil Generation Capacity	46.20%	0.0193	0.65	0.32	0.03
Installed Renewables Aggregated Capacity	99.40%	0.0144	0.23	0.04	0.74

For the statistical values shown in Table 1, the MAE/M variable is the mean absolute error (MAE) divided by the mean (M) of the data. R^2 is the coefficient of determination and measures the point-by-point correspondence of the model output with the historical data. Only the installed renewables capacity variable has a very high R^2 value, since it is the only variable with excellent point-by-point correspondence of the model output with historical data.

A statistical measure, the Theil inequality statistics is used to further confirm the model fit of the historical data and model output. It decomposes the total *mean square error* (MSE) between the model run and real data into three components, U^m, U^s and U^c. These three components arise from the bias (unequal means of simulated and actual data), unequal variances (difference in variance), and unequal covariation (due to point-to-point covariance), and satisfy $U^M + U^S + U^C = 1$. From Table 1, the monthly consumption for the total and most of the various consumption sector variables reproduces the real data behaviour very well with the MSE concentrated in the unequal covariations. This implies that the model variables have the same mean and trends as the historical data, but differ from the historical data point-by-point. The installed renewables capacity has excellent point-by-point correspondence of model and historical data, which is statistically confirmed further by its MSE, concentrated in the “bias” and the “unequal covariation”. The installed fossil capacity reveals a good point-by-point correspondence of the model and historical data and has a level of MSE concentrated in the bias. This implies that the trends are well-represented but there is a slight shifting of the model simulation run from the data. However, this shifting can be ignored since the MAE is only 2% of the average of the historical fossil generation data. Using the Theil statistics measure of these key variables non-systematic errors are elaborated for the model. In this work, the model emulates the historical data very well within the calibration period.

The long-term installed capacities of the various generation technologies for the four scenarios in Section 3 are critically evaluated in the next section. The environmental impact is represented by CO_2 emissions, while the BAU scenario is used as the base for comparative purposes. Both aggressive and more relaxed policies are examined together with their respective impacts on low-carbon generation capacity investments. In addition, the effect of tourism is minimal within our modelling assumptions, they are not separately detailed, but instead contained within a combined scenario analysis detailed in Section 4.3.

4.2 Scenario-Specific Capacity Mix

4.2.1 Installed Fossil Generation Capacity

For various simulation runs of the model for scenarios that double and triple the energy-efficiency target (over the 15-year time-period in which the energy efficiency policy is active) there was negligible influence on the installed fossil generation capacity. Similarly, the trajectory of the installed fossil generation is unchanged by various EV expansion policies ~~together~~. In all cases, the installed fossil generation capacity shows no discernible difference from the BAU scenario for the given installed fossil capacity. The results reveal that only the renewables policy provides an apparently significant effect on the installed fossil generation capacity. The effect is seen especially when renewables policies are driven for longer – see Figure 5.

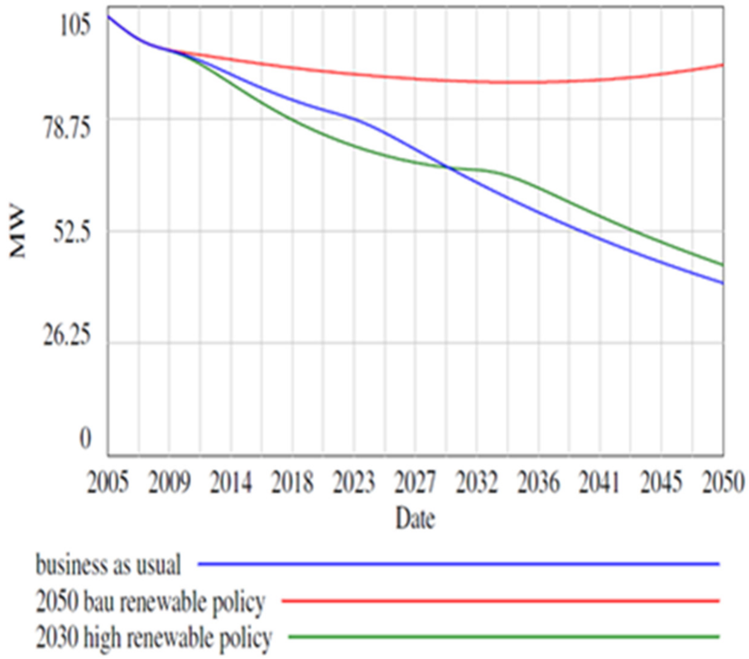

Figure 5 Impact of various renewable policies on installed fossil generation capacity

Figure 5 shows the effects on the installed fossil generation of changing the renewables policy. For the BAU scenario, the renewables policy seeks to have 45% of the 2005 total electricity generation capacity provided by renewables by 2020. This policy also seeks a 30% reduction of the 2005 CO_2 emissions level over the same period. The long-term effect of this policy on the installed fossil generation policy shows a steady decline in such installations from about 103MW in 2005 to about 35MW in 2050. From these results, it is also seen that the 2030 high renewables policy follows a similar downward trend but at a higher rate of decline up to 2030, before tapering off above the BAU scenario. For the 2050 renewables policy, the trend is a slight drop in installed capacity, which then gradually increases, and settles at a slightly lower capacity than the 2005 installation value.

The main conclusion from these results is that the renewables policy will have more of an effect on the installed fossil generation capacity than other potential scenario influences such as the effects of energy efficiency and EV expansion.

4.2.2 Installed Energy Storage capacity

As in the case of the installed fossil generation capacity, the range of energy efficiency scenarios and EV expansion have a negligible impact on the installed energy storage within this island system. The simulation runs for the various scenarios in all cases appear to be congruent with no discernible differences from the BAU scenario.

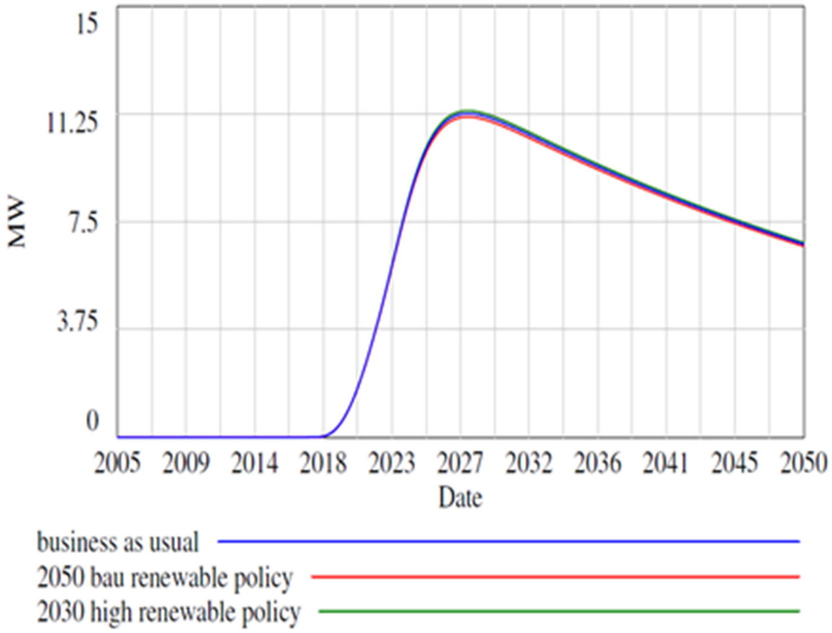

Figure 6 Impact of various renewable policies on installed energy storage capacity

The impact of the various renewables policies on the installed energy storage capacity is also minimal though it still reveals some level of impact as represented by the thicker lines in Figure 6. This can be attributed to the fact that there are separate non-related energy storage policies that guide these installations. However, the minimal impacts confirm that renewables policies do have the potential, in the absence of energy storage policies, to have a long-term influence on the growth of energy storage installations and vice versa.

4.2.3 Installed Renewables Capacity

A focus on the installed renewables within the system sees many dynamics related to the energy efficiency, EV expansion and renewables policies. Figure 7 shows that the effect of the energy efficiency futures on the installed renewables capacity is more pronounced than with the energy storage and fossil generation futures. The installed renewables capacity for the tripling of energy efficiency measure is lower than that of the doubling measure, which is concomitantly lower than the BAU scenario after the 15 years’ timeline for energy efficiency policy. This observation is valid under the assumption that, in the long-term, renewables are the preferred ‘capacity-type’ to be installed. To satisfy the change in the long-term demand there will be a proportional change in the installed renewables capacity. The installation changes are not very visible for the earlier part of the simulation until around 2023, because the installed capacities during those initial years are sufficient to meet the variations in the demand given from energy-efficiency measures. These results reveal that energy efficiency measures will have an impact on the long-term investments and will be directly applicable to the generation technology that is preferred for capacity installations (in this case a low-carbon renewables focus). Consequently, the impact of energy efficiency measures on generation capacity investments is driven by the pre-existing direction of capacity installation policies such as renewables integration.

Additionally, there are various long-term impacts on the installed renewables capacity trajectories visible for the different EV expansion policies. It can be seen that the combined EV expansion market and 2020 policy (grey line) result in a higher renewables capacity by 2050 than is seen in all other scenarios. In addition, for the other scenarios of market-based and only a 2020 EV policy the penetration of renewables has very similar trajectories and hovers around the “business as usual” scenario in the long term. This validates the previous result in (Matthew, 2017) that EV expansion is a key aspect to increasing the renewables capacity of the island system. There is also a small dip in installed renewable capacity around 2027-2032 (more visible with the combined EV expansion and 2020 policy scenarios) for the simulation runs with more EVs (red, green and grey lines). This implies that fewer capacity investments are facilitated up to a point with higher EV penetration (assuming that the EVs have a mainly off-peak charging routine at low-load periods). This result remains valid where renewables capacity is the preferred generation source for new capacity investments as highlighted for the energy efficiency results above.

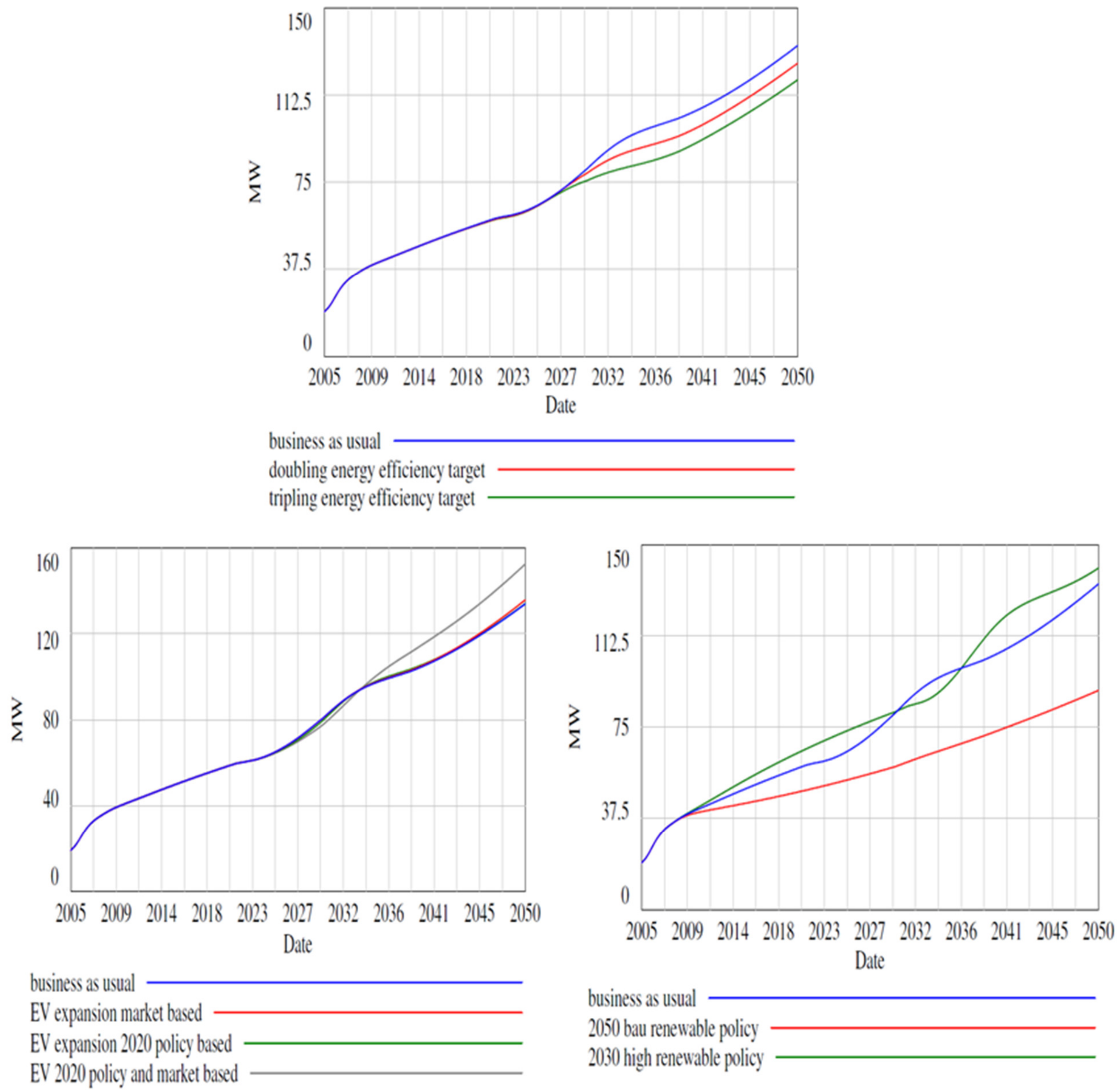

Figure 7 Impact of energy efficiency scenarios (top graph), EV expansion policies (bottom left-hand graph) and various renewable policies (bottom right-hand graph) on installed aggregated renewable capacity

Figure 7 (bottom right-hand graph) also shows the effects of the various renewables policies on the installed renewables capacity. Both the BAU and 2030 high-renewables policy scenarios result in similar trends in the quantities of installed renewables within the system by 2050. In both simulations, they are initially s-shaped curves (as the desired installations that are achieved are followed by further installations to meet the long-term increasing electricity demand). In addition, invoking the notion of SD archetypes, one can say that these s-shaped curves are oscillating after an overshoot (Sterman, 2000, page 121), along an upward trajectory of the installed renewables carrying capacity, whereas the 2050 renewables policy simulation gradually increases installed renewables capacity over the timeline of the simulation to about 90MW in 2050. The 2050 renewables policy extends the renewables capacity and emissions goals of the BAU scenario over the entire timeline, i.e. up until 2050. This scenario run had the lowest rate of installations and resulted in the least amount of installed renewables capacity by 2050. This implies that relaxing the renewables policy has less influence than a more aggressive renewables policy has on substantially increasing the quantities of installed renewables capacity.

4.3 Combined Scenarios Capacity Mix

This section presents a comprehensive consideration of policies and drivers. A simple approach was taken in which all of the aggressive policies and drivers ("all policies high") were simulated at once and compared to all of the less aggressive policies and drivers ("relax all policies") being simulated at once. For example, with the aggressive policies and high driver influences the 2030 high-renewables policy was combined with the high EV expansion and high energy-efficiency measures (18% reduction). As noted earlier a high tourism growth rate was also factored in, but found to have negligible impact (within the assumptions of that putative scenario).

Intuitively it should be expected that a combined scenario analysis might reveal profound systemic observations that may have previously been missed by more limited. In reality, however, we find in this case that the synthesis approach described in this paper reinforces and further clarifies the observations and conclusions that were already visible within the preceding individual scenario-by-scenario analysis (Matthew et al., 2017). This reinforcement of prior observations gives insights into the key issues for the future of the system when all real-world influences and policies are *in situ*. In addition, this combined scenarios approach can be tested more robustly in a Markov Chain Monte Carlo (MCMC) sensitivity analysis to give further model confidence bounds as in Section 4.5. Results for the combined scenario analysis were obtained and compared to BAU for the key variables.

4.3.1 Installed Fossil Generation and Energy Storage Capacity

Figure 8 (left) shows the effects on the installed fossil generation of the different combined scenario simulations. The "relax all policies" simulation produced the most fossil generation capacity in the long term compared to BAU and the "all policies high" simulation produced the least. These results also corroborated the findings distilled from Figure 5, implying that fossil generation is highly influenced by the type of renewable policy that stems from the environmental and energy-security concerns of the system.

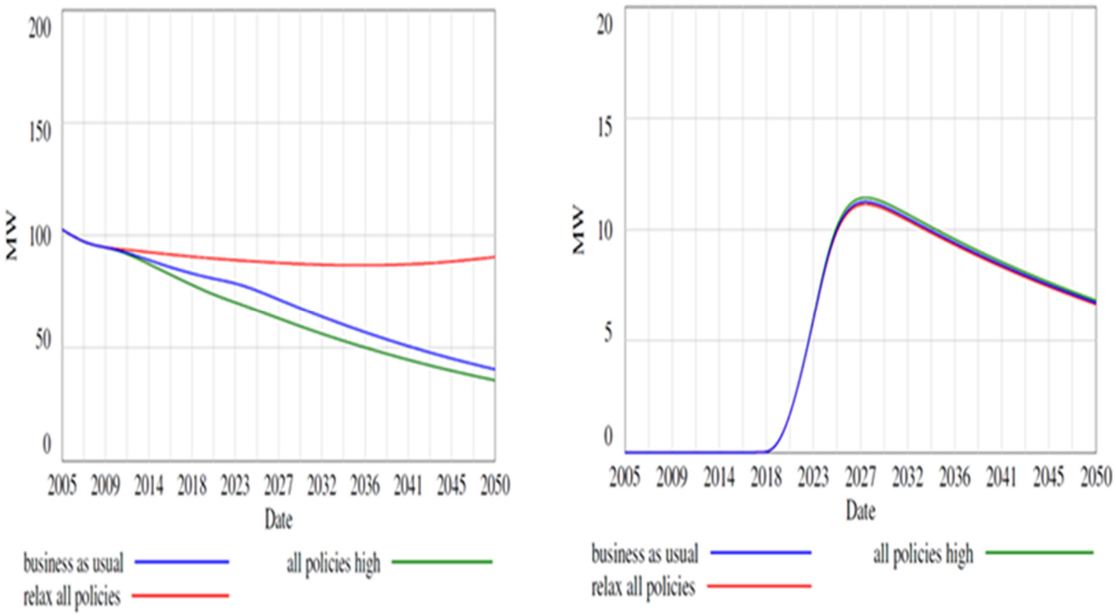

Figure 8 Impact of combined scenarios on installed fossil generation capacity (left) and energy storage capacity (right)

Figure 8 (left) reveals a range of possible futures for fossil-fuel generation but in Figure 8 (right) it can be seen that a very rigid and distinctive evolution of energy storage occurs. This reproduces the behaviour witnessed in all the preceding scenario analyses for the energy storage variable (see Figure 6). In SD analysis, observations of this type are consistent with the influence of a strong external driver and, in this case, it is the policy goal for a small reservoir energy-storage project on the island to commence after 2019. Hence, energy storage within this model is found not to be endogenously driven by model behaviours. The fact that in all scenarios installed energy-storage capacity actually decreases at the end of the policy implies that the policy must be upheld in the long term to sustain energy storage within the system. The result also gives insights that distinct and limited (strict) energy-storage policy goals are not affected by other policies in the system.

That said, it is important to recognize that this SD analysis does not include the possibility of vehicle-to-grid electricity storage, which could become a major component of electricity storage in the future and hence build upon earlier and more traditional policy-led energy-storage approaches. Nevertheless, one can springboard from them, and hence avoid the decline in storage seen in the years after 2025 in Figures 6 and 8 (right). Energy-storage policies should be more aggressive and possibly aligned with other energy policies such as renewables integration within the system.

4.3.2 Installed Renewables Capacity

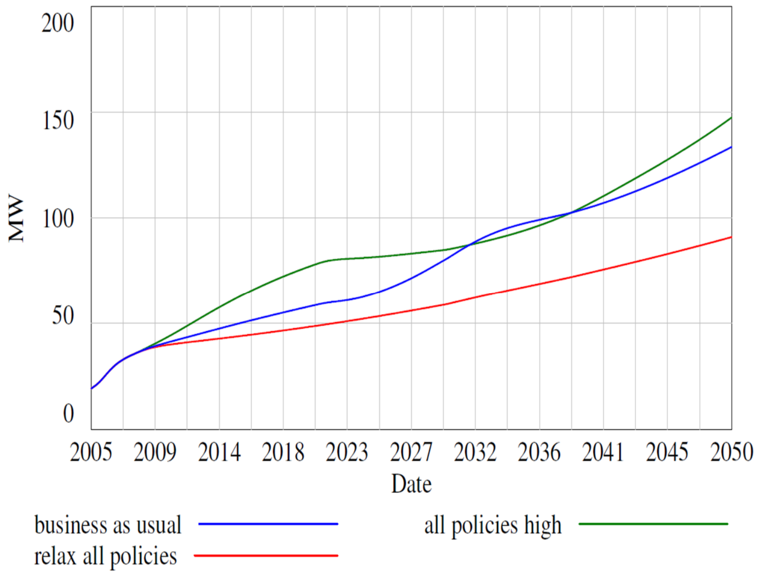

Figure 9 Impact of combined scenarios on aggregated installed renewable capacity

Figure 9 shows the effects of the combined-policies simulation runs on the installed renewables capacity. For these results, "relax all policies" achieved the least amount of installed renewables while conversely the "all policies high" simulation achieved the highest in the long term. The latter also achieved a deeper penetration of renewables driven by the renewables policy and aided by the high influx of EVs (almost 25% more than BAU by 2020) within the earlier years. These results also reflect the advent of energy storage and the high- and low- renewable policy scenario results of Figure 8 (left). This implies, as with the installed fossil generation capacity, that the installed renewables capacity is strongly influenced by the existing renewables policy. The oscillations seen for the renewables-policy scenario in the previous section corroborates the influence of renewables policy on the renewables capacity installed. This is evidenced from the s-shaped archetypes (of the balancing effects) of the various (2030 and 2050) goal-seeking targets of the renewables policy. In addition, it can be seen that a high penetration of renewables can still exist even under high energy-efficiency measures and EV expansion within the system whilst a lower penetration of renewables capacity exists with weak energy-efficiency measures.

4.3.3 Accumulated CO_2 Emissions

Figure 10 shows the corresponding impacts of the combined scenarios simulations on the long-term accumulated CO_2 emissions. The BAU and "all policies high" simulations achieve comparable CO_2 emissions by 2050, while emissions are greatest in 2050 (80% to 90% more than in other runs) for "relax all policies". The "all policies high" scenario is able to mitigate the long-term increases in CO_2 emissions and achieves the lowest level by 2050.

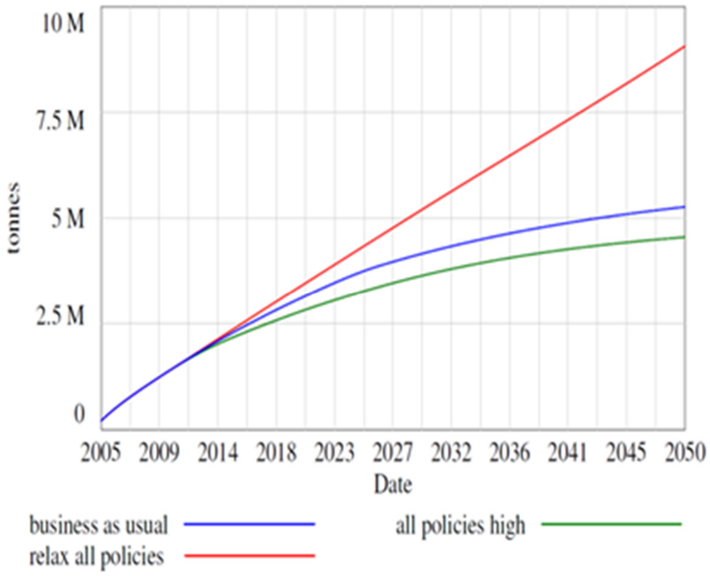

Figure 10 Impact of combined scenarios on accumulated CO_2 emissions

These results indicate that pursuing non-aggressive energy policies in the island system hinders both environmental and energy security objectives and leads to greater electricity challenges for energy transition. However, these policies are not overly aggressive since similar environmental objectives can still be achieved by adopting the BAU policy. Thus, balancing environmental and energy-security concerns is vital and strongly influences both the pathway and investment polices required to alleviate them.

4.4 Long-term Profitability Impacts on Capacity Investments

It was observed earlier that the policies for renewables installation are very influential within the system and the installed capacity can exhibit s-shaped growth with overshoot and oscillations (Sterman, 2000). Here the financial attractiveness linked to the profitability of the installed capacities is used to gauge the impacts within the installed capacities of the system. The only difference from the previous analysis is the use of high electricity tariffs for the BAU scenario (fixed at double the 2005 tariffs). This should reflect a situation in which the utility company can collect more revenues for their equivalent sale of electricity capacity.

Figure 11 displays, through various runs, the sensitivity of the increased profitability on the investments in the different installed capacities. The investments in energy storage exhibit no change in capacity investments with high electricity tariffs. This is again due to the fixed energy-storage policy for capacity, so no investments are made with excess revenues available. Also shown is the fossil generation investments’ downward trajectory which is unchanged though there is a greater delay in the removal of fossil generation from the system due to installed fossil generation remaining more financially attractive than in BAU because of the higher financial prosperity to the electricity company from the excess revenues collected.

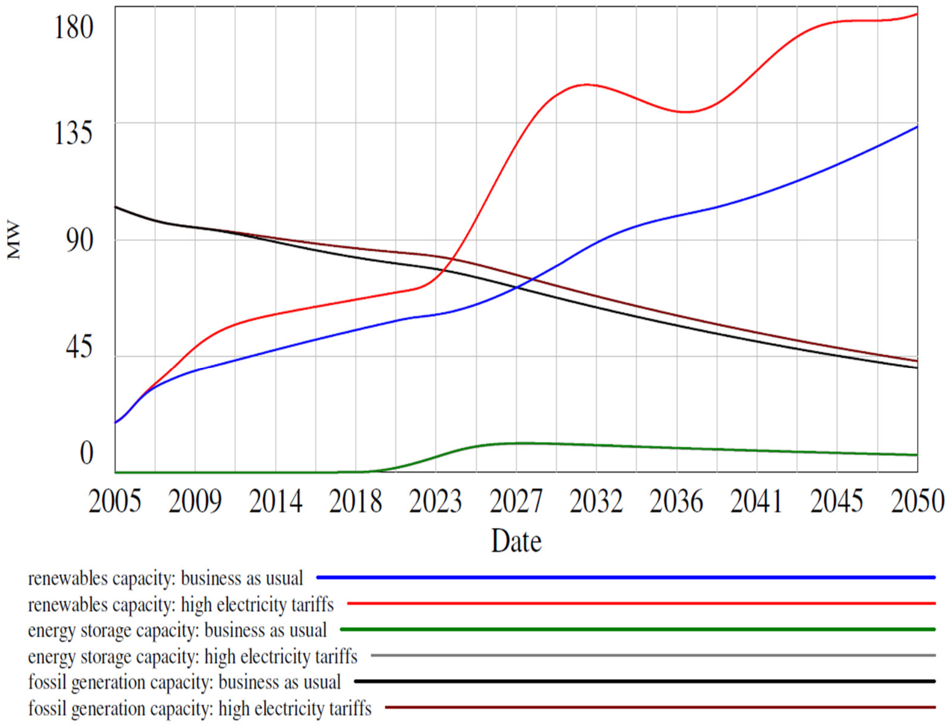

Figure 11 Impact of increased profitability on installed capacity

For the installed renewables capacity (blue and red lines), the investments increases under high electricity tariffs and a lot more renewables-capacity installations occur in the long-term by 2050. A more prominent s-shaped growth with an overshoot SD archetype (Sterman, 2000) is also visible. The red curve has pronounced periods of high renewables growth before encountering a slowdown and this observation recurs for the entire simulation. These oscillations, however, become damped which indicates that there is some local stability for the trajectory of the installed renewables capacity. A strong indicator that the cycles necessary for the renewables investments is constrained by a negative feedback is probably linked to the financial upkeep of the new installations. Additionally, this phenomenon might be also related to the environmental and energy-security driven renewables policy goals of the system. Taking this into account, it can be said that the financial viability of the electricity company can provide for a greater penetration of low-carbon, however, the low-carbon policies need to focus on the more rapid damping of likely oscillations (as shown in the BAU results). These challenges are all mitigated with the correct approach to the low-carbon transition in terms of suitable investments and innovative business models for the utility company to avoid a boom-and-bust-cycle effect for new low-carbon generation.

4.5 Long-term Capacity Mix Confidence Bounds

This section details the results on the confidence bounds of the installed capacities for disaggregated renewable sources together with the fossil generation. In addition, the confidence bounds for the accumulated CO_2 emissions are displayed. These results are obtained by applying the standard Vensim multivariate MCMC sensitivity analysis to the policy scenarios discussed in Section 3. Two hundred simulations were conducted, with the program randomly selecting values from the sensitivity ranges of the parameters shown in Table 2. The switches (for turning on and off policy/specific implementations within the model using a binary (1) on and (0) off) used for model implementation in the Vensim software for the EV expansion were also activated.

Variable Name/ **Unit**	Base value	Sensitivity ranges	Reference data
avg consumption per tourist-night stays/ **MWh/night stays**	0.0027	0.0020 - 0.0035	http://www.onecaribbean.org/content/files/CHENACT%20-CREF.pdf
tourist stays growth rate/**%/Month**	0.14	0.07 - 0.28	SREA,2018
energy efficiency reduction/**%**	6	6 - 18	http://ec.europa.eu/regional_policy/archive/activity/outermost/doc/plan_action_strategique_eu2020_acores_en.pdf/
renewables policy portfolio/**%**	0.45	0.45 - 0.55	Authors' own elaboration
renewables policy timeline/**Months**	156	156 - 506	http://ec.europa.eu/regional_policy/archive/activity/outermost/doc/plan_action_strategique_eu2020_acores_en.pdf/
CO_2 emissions target/**Months**	0.3	0.3 – 0.5	http://ec.europa.eu/regional_policy/archive/activity/outermost/doc/plan_action_strategique_eu2020_acores_en.pdf/
time to meet EU CO_2 emissions target/**Months**	180	180 - 540	http://ec.europa.eu/regional_policy/archive/activity/outermost/doc/plan_action_strategique_eu2020_acores_en.pdf/

Table 2 Important variables for the sensitivity analysis

The results displayed in Figure 12 show the confidence bounds as coloured bands using the 50%, 75%, 95% and 100% percentiles. So for example, a 75% confidence bound (green) indicates that 75% of all runs fall within the top and bottom green bands (including obviously the 50% yellow band), 90% within the blue bands and 100% within the grey bands. The resulting range of possible outcomes for the capacity installations of the different technologies and the accumulated CO_2 emissions of the system under the given ranges of these policies are shown in Figures 12, 13 & 14.

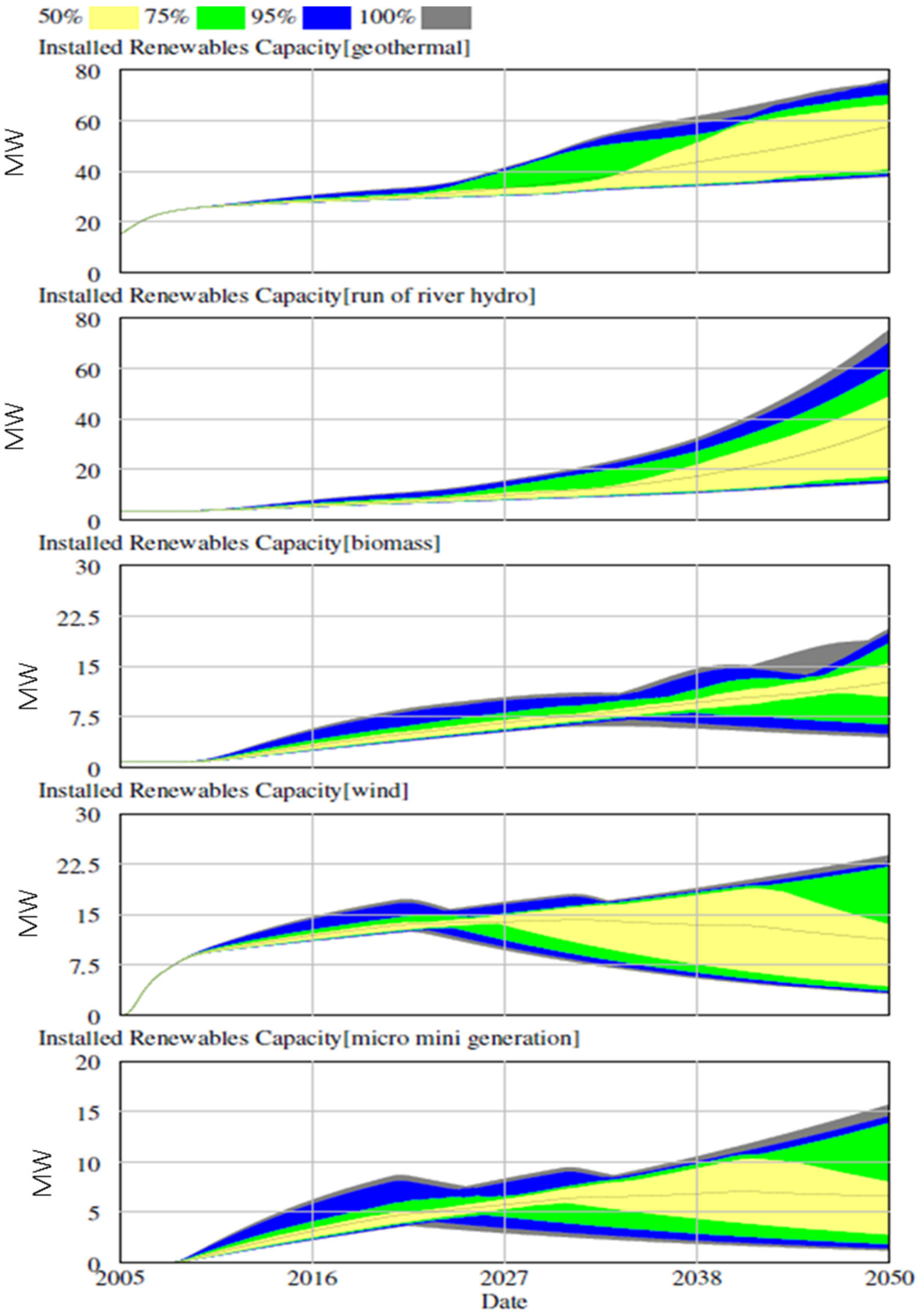

Figure 12 Sensitivity of the installed disaggregated renewables capacity

Figure 12 displays the range of MW values for the installed capacities of the disaggregated renewables capacity of the system. The base-load renewables such as geothermal and run-of-river hydro have the largest installed capacities with the former bounded within a higher range than the latter. The other renewables such as biomass, wind and micro/mini generation (solar) are bounded within lower ranges of installed capacities. This implies that the base-load renewables will be more prominent in the longer-term than the more intermittent renewables. (The limits to their installations can be restricted by the availability of the respective heat and water resources within the island.) Although biomass is not an intermittent renewable source it struggles to compete with the more familiar ~~(learning-by-doing)~~ and cost-effective base-load renewables.

Figure 13 captures the range of possible outcomes for installed fossil generation. It confirms that, in the long term, there will be a decrease in capacity from fossil generation, implying any combination of the assorted policies in Section 3 will lead to lower fossil generated capacity by 2050.

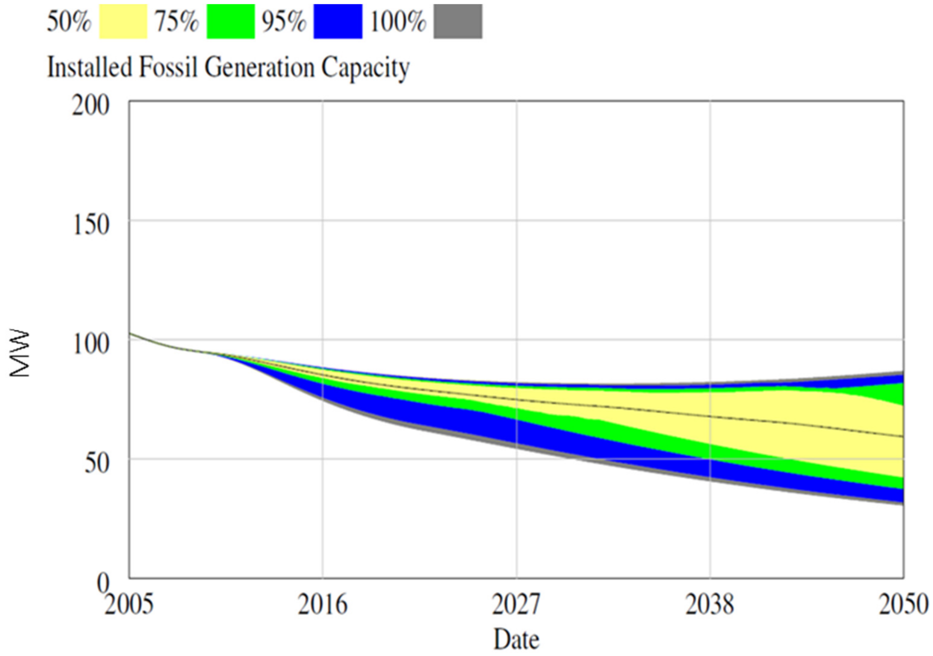

Figure 13 Sensitivity of the installed fossil generation capacity with various policies

Also observed is the wide range of installed fossil generation by 2050, which implies that the policies applied for the removal of fossil generation must be closely aligned to the lower range of possible outcomes (driven by the renewables policy) in Figure 13.

Figure 14 presents the range of possible outcomes for the accumulated CO_2 emissions until 2050. The wide extent of possible outcomes is guided by the large range of possible outcomes of the installed fossil generation within the system. It indicates that, with a higher installation of fossil generation (from more relaxed low-carbon policies), CO_2 emissions can be as high as 8 million tonnes or it can be as low as 4 million tonnes with a lower level of fossil installations.

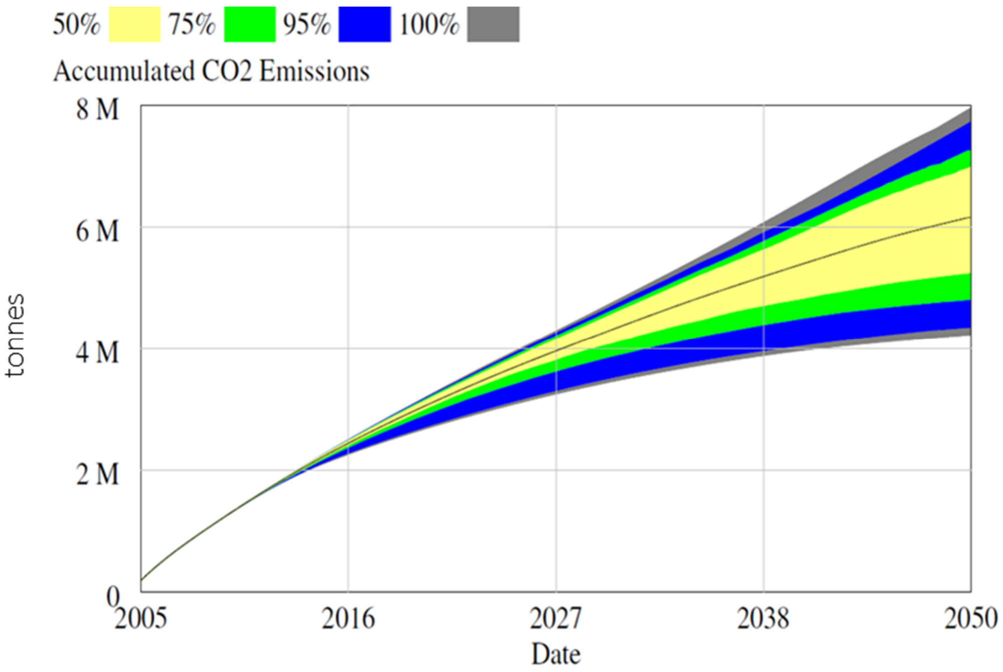

Figure 14 Sensitivity of the accumulated CO_2 emissions with various policies

This reinforces the judgement that co-ordinated policies must be pursued to minimise the environmental challenges and effects of CO_2 emissions, i.e., those that keep installed fossil generation lower. These confidence bounds for the policy scenarios give a view of the wide-ranging possible outcomes that each of the key variables examined can experience in the long term.

Figure 15 focuses on the differences seen between 2005 and 2050 for three key outputs of the model. In each case three distinct policy contexts, or scenarios, are considered. These are as described earlier and in each case an assumption is made that the relevant scenario has been followed for the full 45-year period yielding the 2050 result presented in the figure. The figure reveals very clearly a significant decline of fossil fuel combustion in both the Business-As-Usual and All-Policies-High scenarios, but we see that, in the case of the All-Policies-Relaxed scenario, significant fossil fuel use remains. We see that renewable generation grows significantly in all scenarios, although it is somewhat lower in the All-Policies-Relaxed scenario. This is unsurprising given the continued significance of fossil fuels in that scenario. Earlier we observed that it is renewables policy that shapes fossil-fuel developments rather than the other way round. In all cases greenhouse-gas emissions reduce significantly and this is broadly consistent with international policy goals. The most dramatic emissions reduction is seen in the All-Policies-High scenario (approximately 21,400 Tonnes per annum in 2050, as opposed to more than 30,000 Tonnes per annum in both the other two scenarios).

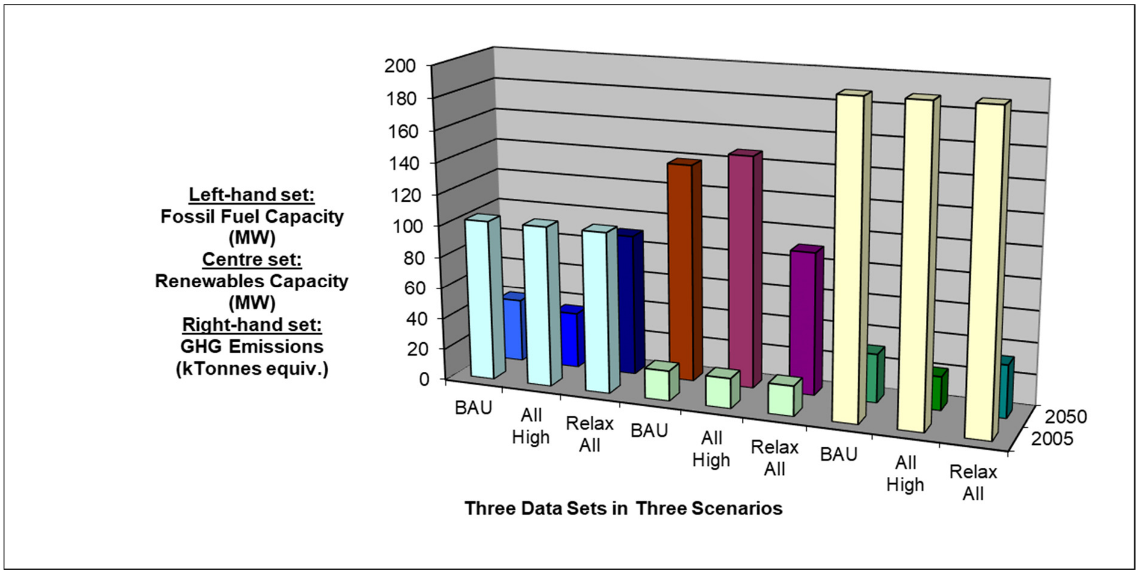

Figure 15 A summary representation of the changes from 2005 to 2050 seen for three key model outputs: installed fossil fuel generation capacity, installed renewable electricity capacity and annual greenhouse gas emissions. The 2050 data represents central values in the three policy scenarios described in the text (Business As Usual, All Policies High, and All Policies Relaxed). For each model output, the historical 2005 data is not affected by the future scenario pathways.

5. Conclusions

This paper presents a new SD simulation model of electricity capacity investments and policy influences for a low-carbon electricity system. The model captures key causal relationships, including environmental and energy security issues, for an isolated island electricity system. The model represents endogenous demand dynamics arising from low-carbon policies. It also includes policy barriers and consideration of the incentives required for more sustainable electricity systems. Additionally, the model has the potential to inform electricity policy planning. It gives particular insight into possible approaches to investments in electricity-generation capacity expansion.

To be more specific the model reveals that the low-carbon policies of EV uptake and renewables electricity- generation are important especially as related to the potentially beneficial synergies between both developments. Indeed, high EV penetration gives the largest installed renewables capacity in 2050. In contrast, the high-efficiency scenario has the lowest deployed renewables capacity in 2050 of all the scenarios considered. The difference between highest and lowest renewables capacity is 30% of the maximum capacity seen. EV expansion can permit a short-term reduction in generation capacity investments of 5-10% compared to a Business-as-Usual future. This is compatible with trajectories increasing the amount of installed renewable generation capacity in the longer-term. Meanwhile, fossil-fuel-based generation capacity will be largely eliminated from the generation mix over the long term especially as near baseload renewables, such as geothermal and run of river hydropower, assume a greater role ahead of more variable sources (e.g. wind generation). The island of São Miguel is blessed by having access to substantial renewable sources of various types – near baseload, dispatchable and variable/intermittent.

The model reveals that CO_2-emissions reductions of up to 50% are readily possible. Island systems, in particular, show us that energy-storage policies are vital in enabling high-renewable generation futures. To that end relevant policies need to be more aggressive and better aligned with each other to support the deployment of more electricity-storage capability. The model shows that a mix of low-carbon policies can be especially useful for isolated island systems because renewables policies alone can even act to dampen renewable capacity investments in some scenarios. Supporting policies (e.g. in storage or EVs) are needed for the highest renewable capacities to be realised – renewable energy policy alone is not sufficient and can even become detrimental to progress.

The model shows, unsurprisingly, that less ambitious energy-storage policies do indeed yield lower energy-storage capacities in the long term than can be achieved in other policy contexts. Policy, of course, is not the only determinant of investment; for example, the financial viability of the electricity system can shape the installed capacity of low-carbon generation especially in scenarios with weak, or non-existent, low-carbon policies.

As noted above, the model reveals the synergistic benefits between policies for renewable energy, EVs and electricity storage. Electricity-storage systems are not just involved in ensuring ongoing energy supply and demand balance they are also important over short timescales in protecting the frequency of the electricity system. While there has been much work recently on concepts of "virtual inertia" for renewables-dominated grids, more traditional solutions such as flywheels are also available. Recent innovations in low-carbon frequency-balancing generation sources have been reported by Martínez-Lucas *et al.* (2016), Inoue, Genchi and Kudoh (2017) and Muñoz-Benavente *et al.* (2017).

The work reported in this paper reveals the extent of technical opportunities, the power and reach of policies, and the synergistic interactions between technologies and policies. The research can additionally be used to inform future policies, in particular showing the opportunities that policy makers have to shape the development and future of low-carbon isolated electricity systems. To be more specific, the results indicate that renewable targets are of significant importance for ensuring emissions reductions and such policies have a key role in achieving an expansion of low-carbon capacity within the electricity system. An EV expansion policy, of appropriate scope and duration, and such as may be aided by governmental intervention, can enhance the uptake of low-carbon generation in the long term and can defer by 5-10% the need for further capacity investments. Energy-storage policies are best when applied more aggressively and the greatest benefits come from an alignment with other energy and environmental policies. Generally, sustained policies are more effective than sudden initiatives or time-limited measures. Policy makers can build upon more traditional energy-security measures (including storage) and springboard from them into encouraging new technologies. In the future, such initiatives might include EVs as grid storage and new and smarter frequency-balancing capabilities.

Adopting a SD approach confirms that a whole-system overview provides benefits in terms of insight and understanding over more disaggregated approaches to policy. The work reported here for an island system shows that one needs to be cautious especially of applying overly narrow policy approaches towards complex environmental and energy-security objectives, for which a portfolio approach of policies can be expected to be more effective and efficient.

References

Baptista, P., Camus, C., Silva, C., Farias, T., 2009. Impact of the Introduction of Electric Based Vehicles in São Miguel Island, in: Second International Symposium on Engineering Systems. Cambridge, MA.

Bass, F.M., 1969. A New Product Growth for Model Consumer Durables. Manage. Sci. 15, 215–227. https://doi.org/10.1287/mnsc.15.5.215

Bompard, E., Connors, S., Fulli, G., Han, B., Masera, M., Mengolini, A., Nuttall, W.J., 2012. Smart Energy Grids and Complexity Science, Joint Research Centre Scientific and Policy Reports. https://doi.org/10.2790/69368

Botelho, F., 2015. Electricidade dos Açores.

Chappin, É., 2011. Simulating Energy Transitions, PhD Thesis. Next Generation Infrastructures Foundation. https://doi.org/ISBN: 978-90-79787-30-2

EDA, 2016. Electricidade dos Açores [WWW Document]. URL http://www.eda.pt/Paginas/default.aspx (accessed 8.16.14).

EDA, 2008. Electricidade dos Açores, Caracterização da Procura e da Oferta de Energia Eléctrica 2009-2013 [WWW Document]. URL http://www.eda.pt/Investidores/Rating/EDA 2009 2014.pdf (accessed 8.16.16).

European Commission, 2016. Low Carbon Technologies [WWW Document]. URL http://ec.europa.eu/clima/policies/lowcarbon_en (accessed 10.12.16).

European Commission, 2013. The Autonomous Region of the Azores [WWW Document]. URL http://ec.europa.eu/regional_policy/sources/activity/outermost/doc/plan_action_strategique_eu2020_acores_en.pdf (accessed 2.2.14).

European Commission, 2019. Energy security strategy. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/energy-security-strategy

Forrester, J.W., 1961. Industrial dynamics. M.I.T. Press, Cambridge, Massachusetts.

Foxon, T., 2013. Transition pathways for a UK low carbon electricity future. Energy Policy 52, 10–24.

https://doi.org/10.1016/j.enpol.2012.04.001

Foxon, T.J., 2011. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. Ecol. Econ. 70, 2258–2267. https://doi.org/10.1016/j.ecolecon.2011.07.014

Franco, A., Vieira, N., Ponte, C., 2017. Geothermal developments in Pico Alto, Terceira Island, Portugal.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Policy 36, 399–417. https://doi.org/10.1016/j.respol.2007.01.003

IEA, 2016. Key Electricity Trends Electricity Summary [WWW Document]. Excerpt From Electr. Inf. URL http://www.iea.org/statistics/topics/electricity/%5Cnhttp://www.iea.org/t&c/termsandconditions/

Ilic, M., Xie, L., Liu, Q., 2013. Engineering IT-Enabled Sustainable Electricity Services: The Tale of Two Low-Cost Green Azores Islands. Springer Science & Business.

Inoue, M., Genchi, Y., Kudoh, Y., 2017. Evaluating the Potential of Variable Renewable Energy for a Balanced Isolated Grid: A Japanese Case Study. Sustainability 9. https://doi.org/doi:10.3390/su9010119

IEA, 2019. Energy Security. International Energy Agency. https://www.iea.org/topics/energysecurity/

IRENA, 2014. A Path to Prosperity: Renewable Energy for Islands.

IRENA, 2013. Renewable Power Generation Costs in 2012: An Overview.

Islands Energy Program, 2016. Statement of qualifications [WWW Document]. URL http://carbonwarroom.com/content/islands-energy-program#impact (accessed 10.14.16).

Isle-pact, 2012. Island sustainable energy action plan, Sustainable energy action plan Azores Archipelago [WWW Document]. URL http://www.islepact.eu/userfiles/ISEAPs/Report/azores/Azores ISEAP_V10.5_EN.pdf (accessed 9.1.16).

Martínez-Lucas, G., Sarasúa, J.I., Sánchez-Fernández, J.Á., Wilhelmi, J.R., 2016. Frequency control support of a wind-solar isolated system by a hydropower plant with long tail-race tunnel. Renew. Energy 90, 362–376. https://doi.org/10.1016/j.renene.2016.01.015

Matthew, G.J., 2017. Sustainable Low-Carbon Isolated Island Electricity Systems - Policy and Investment Impacts Assessed using System Dynamics. The Open University.

Matthew, G.J., Nuttall, W.J., Mestel, B., Dooley, L., 2015. Insights into the Thermal Generation Futures of Isolated Island Electricity Systems Using System Dynamics, in: 32nd International Conference of the System Dynamics Society. Cambridge, MA.

Matthew, G.J., Nuttall, W.J., Mestel, B., Dooley, L., 2014. Simulating the development and utilization of autonomous smart grid systems using system dynamics, in: PhD Colloqiuim at the 31st International Conference of the System Dynamics Society. Delft, Netherlands.

Matthew, G.J., Nuttall, W.J., Mestel, B., Dooley, L., Ferrão, P.M., 2016. Renewable integration in island electricity systems—a system dynamics assessment, Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-319-29643-2_8

Matthew, G.J., Nuttall, W.J., Mestel, B., Dooley, L.S., 2017. A dynamic simulation of low-carbon policy influences on endogenous electricity demand in an isolated island system. Energy Policy 109, 121–131. https://doi.org/10.1016/j.enpol.2017.06.060

MIT, 2011. The Future of the Electric Grid, An Interdisciplinary MIT Study. Mit. https://doi.org/ISBN 978-0-9828008-6-7

Muñoz-Benavente, I., Gómez-Lázaro, E., García-Sánchez, T., Vigueras-Rodrígue, A., Molina-García, A., 2017. Implementation and assessment of a decentralized load frequency control: application to power systems with high wind energy penetration. Energies 10, 151. https://doi.org/doi:10.3390/en10020151

Nunes, J.M., 2015. Azores Regional Directorate for Energy.

Nuttall, W.J., 2013. Energy: Looking Over the Horizon some thoughts and observations.

Parness, M., 2011. The Environmental and Cost Impacts of Vehicle Electrification in the Azores. MIT.

Pina, A., Silva, C., Ferrão, P., 2012. The impact of demand side management strategies in the penetration of renewable electricity. Energy 41, 128–137. https://doi.org/10.1016/j.energy.2011.06.013

Silva, M., 2013. Energy planning with electricity storage and sustainable mobility: The Study of an

Isolated System. University of Porto, Portugal.

SREA, 2018. Regional Statistics Services of the Azores [WWW Document]. URL http://estatistica.azores.gov.pt/default.aspx?lang_id=2 (accessed 6.26.18).

Sterman, J.D., 2000. Business Dynamics : Systems Thinking and Modeling for a Complex World, Irwin/McGraw-Hill. Boston, Mass.

UNF, 2013. Achieving Universal Energy Access [WWW Document]. URL http://www.unfoundation.org/what-we-do/issues/energy-and-climate/clean-energy-development.html (accessed 7.2.14).

United States Environmental Protection Agency, 2019. Summary of the Energy Independence and Security Act: Public Law 110-140 (2007). https://www.epa.gov/laws-regulations/summary-energy-independence-and-security-act

UNFCCC, 2016. First steps to a safer future: Introducing The United Nations Framework Convention on Climate Change [WWW Document]. URL http://unfccc.int/essential_background/convention/items/6036.php

Vallvé, X., 2013. Renewable Energies for Remote Areas and Islands (REMOTE), in: Microgrids Symposium. Santiago.

Ventana Systems, 2018. Vensim Software [WWW Document]. URL https://vensim.com/vensim-software/ (accessed 3.18.16).

Weisser, D., 2004. On the economics of electricity consumption in small island developing states: a role for renewable energy technologies? Energy Policy 32, 127–140. https://doi.org/10.1016/S0301-4215(03)00047-8

World Energy Council, 2016. World Energy Trilemma 2016: Defining measures to accelerate the energy transition [WWW Document]. URL https://www.worldenergy.org/publications/2016/world-energy-trilemma-2016-defining-measures-to-accelerate-the-energy-transition/ (accessed 5.20.17).

Acknowledgements

This paper is dedicated to the late Steve Connors, an inspiration who help shaped this work with his initial insights and expertise in the area of smart grids and energy policy. In addition, the authors would like to thank Pedro Carvalho, Manuel Heitor, Maria Ilić, João Martins de Carvalho, Julia

Bouchinda and André Pina for helpful academic advice and discussions. We are also grateful to personnel at Electricidade dos Açores (Francisco Bothelo, Paulo Bermonte, and Fernando Martins) and at the Energy Directorate of the Azores (José Nunes and his team) for access to the data and information needed to undertake this study.

Funding:

This work was supported by a PhD studentship from the Faculty of Science, Technology, Engineering and Mathematics of The Open University.

Vitae

George Jr. Matthew works for the Public Utilities Regulatory Commission in Grenada and is a sustainable energy expert. He was previously employed as a post-doctoral researcher attached to the Renewable Energy Group at the University of Exeter, where he provided research expertise within an EU funded project, Intelligent Community Energy, which aimed to develop smart and sustainable energy solutions for isolated communities. George holds a BSc in Mathematics and Physics with postgraduate studies in Electrical Engineering focused on a Wireless Communications specialization. He recently completed his PhD at The Open University, which resulted in a novel System Dynamics (SD) policy and investment analysis framework to improve decision making for next generation low-carbon island electricity systems.

William J. Nuttall is Professor of Energy at The Open University, based in Milton Keynes, UK. Professor Nuttall's career has taken him from experimental physics (PhD MIT USA 1993) to technology policy with an emphasis on energy policy. He is Open University lead for the Imperial-Cambridge-Open Centre for Doctoral Training in nuclear energy; he is Honorary Editor and Chair of the Editorial Panel for the Proceedings of the Institution of Civil Engineers – Energy; and he is a Fellow of Hughes Hall Cambridge. He has extensive policy advice experience for the UK Government and the European Union.

Benjamin Mestel is an applied mathematician working at the Open University in the UK. A specialist in nonlinear dynamical systems, particularly the renormalization theory of critical phenomena, he obtained his PhD at the University of Warwick. Benjamin developed an interest in the applications energy systems while working as Deputy Director of the Isaac Newton Institute for Mathematical Sciences in Cambridge. In addition to the modelling of future energy systems, Benjamin has an interest in the optimal use of storage in low-carbon energy systems.

Laurence S. Dooley is Professor of Information and Communication Technologies at The Open University in the UK. His current research interests include: next generation multimedia technologies, cognitive radio networks, Mobile ad-hoc network security, video coding and island low-carbon electricity systems. He has published 1 book and more than 275 scientific journals, conference papers, book chapters and monographs, with demonstrable esteem via 5 International Best Paper prizes. He is a Chartered Engineer, Fellow of the BCS, Associate Editor of IET Image Processing journal and Vice President of the Welsh Crawshays Rugby Club.