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Renewable integration in island electricity systems – a system dynamics assessment

George Matthew¹, William J. Nuttall¹, Ben Mestel¹, Laurence Dooley¹ and Paulo Manuel Ferrão²

Abstract. Island electricity systems tend to rely heavily on the use of fossil fuels for the everyday supply of customer needs, so there are both significant economic and environmental benefits from the decarbonisation of these systems. One such key global environmental benefit is the anticipated reduction in CO₂ emissions and its associated effects on climate change. In recognition, many islands are already pursuing ambitious goals for renewable energy sources integration. The resulting effects of policy on the long-term investment decisions however, need to be better understood. This paper presents a system dynamics simulation model which evaluates the adoption and diffusion of renewable generation sources within an existing island electricity system. In particular, renewable sources within the Azorean island of São Miguel are considered, with findings revealing that the requisite long-term investments are framed by the local experience of the renewable technologies and the pursuit of further renewable integration policy targets.

Keywords: Renewable Integration. Island Electricity Systems. System Dynamics.

1 Introduction

This paper focuses upon the opportunities and challenges facing those making investment decisions for the integration of renewable sources; to obtain a better understanding of the resulting future portfolio of electricity generation mixes and the possible benefit of these to stakeholders. To streamline the research objective, attention is focused upon an island system where technical issues are small in scope and largely local, but the political economy is largely external. In [1], an extensive review of renewable integration into island systems is presented, which recommends that future models of such systems should incorporate both regulatory environments and the dynamics of learning curves of renewable sources, in order to comprehensively evaluate investment implications in the short, medium and long term. It is also important to identify the drivers and necessary investment and policy insights for a low-carbon optimized system, to achieve a sustainable future. Furthermore key stakeholders can elicit what are the distinct policy drivers and determine beneficial solutions and/or long-term investment strategies.

Several island-based studies have previously been conducted to investigate renewable integration challenges. For example, the island of Flores in the Azores has been used in the study in [2], as a “green” island paradigm characterized by high renewable energy penetration. A TIMES MARKAL analysis model was developed with exogenous demand growth, and a scenario-based approach used to find optimal solutions for energy system design and management, given the different possible

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exogenous ‘evolutions’ of electricity demand. The study analyzed the impact of demand side management (DSM) options, such as energy efficiency measures and dynamic demand response, showing that load shifting strategies could delay new investments, while rendering the current investments on renewable resources more economically viable. Of similar scope is the energy storage study in [3], again for the Azores, which used a least-cost unit commitment model analysis to determine the expected cost savings from introducing energy storage into existing electrical power grid networks. The study highlighted some challenges and revealed potential cost-savings from incorporating energy storage within a smart electrical power grid system. Another study [4], examined the use of electric vehicles for CO₂ emissions reduction by using renewable energy sources as the sole generation supply for charging the vehicles, with a least-cost economic dispatch and unit commitment model being proposed. Parness, also undertook a least-cost economic dispatch and unit commitment model. Recently [5]–[7] used system dynamics to analyze the distributed integration of renewable energy sources, carbon policy incentives and taxation within large interconnected energy networks. These works provide recommendations to policy makers for the uptake of, and pricing patterns for, tradable green certificates and carbon emissions prices. These models rely heavily on historical data, with the dynamics of the system being able to provide useful insights into these types of systems.

System dynamics is not an optimization methodology but rather it aids in understanding and gaining insights into complex systems, by capturing a system’s key feedback structures and important sources of inertia and delays. Key endogenities are often revealed which afford useful insights into the complex system structure and dynamic behaviors. System dynamics can elucidate scenarios and reveal hitherto unexpected behavior and phenomena in response to policies. The model presented in this paper highlights the necessary investment decisions needed to achieve the system’s local renewable target; globally influenced CO₂ emissions targets; and to embed local learning experience of renewable technologies. Long-term sustainability policy interventions tied to these aspects of the system are also explored via the model. The model analyses the scenarios in which the rate of renewable integration is likely/not likely to be delayed, diluted, or defeated by unanticipated reactions and side effects. This becomes evident as the renewable goals are achieved and the learning curves reducing the cost of the renewable investments come into play.

Pruyt and Kwakkel, [8] incorporated learning curves when using system dynamics to consider cost reductions accruing from the experience gained from previous installation of various competing energy technologies. The authors demonstrated the impact of learning curves on the cost of these competing technologies in energy transitions. In [9] the system dynamics approach was further applied to understand holistically the diffusion of a new technology, namely wind power. The authors showed the extent to which system dynamics captures the underlying mechanisms of diffusion processes and applied this to a large interconnected energy system. This provided the context for the case study into our chosen island: São Miguel in the Azores.

The rest of this paper is organized as follows: Section 2 presents the case study used for this work. The developed island renewable integration model is detailed in

Section 3. Sections 4 details the scenarios and Section 5 discusses the initial findings, analysis, validation and insights gained. The paper concludes with Section 6 and includes an outlook of the next steps and future modifications of the model.

2 Case Study: São Miguel – an electrically isolated island

The Azores are an archipelago of nine Portuguese islands about 1,500 km west of mainland Portugal within the Atlantic Ocean. The islands are clustered into three major groups: the eastern, central and western groups, and they have a total population of 245,000 [10]. São Miguel is the largest island in the Azores, both in terms of size and population. It was chosen for this study because it is an electrically isolated island system that has ongoing extensive renewable technologies integration and plans for more in the face of high amounts of fossil fuel generation capacity, partly due to its carbon lock-in [3], [11].

São Miguel's electricity system is isolated in a technical, but not in a political and economic sense. The power system on the island is stand-alone without any interconnections to other islands or the mainland (preventing the import and export of electricity in peak supply and load situations). The island does not operate an energy market and it is dependent on the Portuguese mainland government to determine energy prices and policies [12], [13]. The local electricity company, *Electricidade dos Açores (EDA)*, serves all nine islands including São Miguel as a fully-regulated utility. São Miguel electricity customers pay the same retail electricity rates as mainland Portugal according to national law. Effectively, the Azorean electricity tariffs are subsidized by the rest of Portugal [3]. Policy requires that EDA follows least-cost planning procedures when investing in capacity additions or other grid enhancements. However, as highlighted in [14], and typical to most island electricity systems, São Miguel has a very large capacity reserve margin (well above 30%). In contrast, the UK has a National Grid reserve margin goal of about 20%. As a consequence of the high margin in São Miguel a significant amount of generation capacity is idle most of the year [15]. The annual electricity consumption load grew more than 3% a year in the period 2005-2009, before dropping back after the global financial crisis (not featured in our model). Our model currently assumes that the future demand keeps rising by the same 3% margin, with a fixed set of projected investments which will be responsible for covering additional electricity consumption [12]. The tariff prices for electricity are also expected to rise [13]. Issues of demand will be advanced in future work. In this study demand is exogenous and smoothly increasing.

A key aspect of this study is the recently imposed Portuguese national decree to achieve 75% renewable electricity on the island by 2018, with an intermediate goal of 50% renewable by 2015 [3]. However, there are no clear insights into the long-term dynamics for hastily adopted renewable policies. Would it be delayed, diluted or frustrated due to the global pressures of CO₂ emissions reduction or affected by the local learning curve of the renewable technologies? This paper provides clear insights into this issue as it details the key socio-techno-economic aspects of the renewable integration problem for a typical island electricity system.

3 Renewable integration model

The integration of renewables in the island electricity system raises many uncertainties and different types of complexities and dynamics. As with all complex systems, the structure of the system affects its behavior. The system dynamics approach proposed in this paper makes it possible to represent the dynamics of the system in terms of the “feedback” processes, stock and flow structures, time delays and accumulations. These dynamics arise from the interactions within the networked feedbacks (loops) of the system. There are various causal relationships between key system variables which can be either positive (+ve)/self-reinforcing or negative (–ve)/self-correcting feedbacks. Accumulations are the individual stocks or measurable quantities of the system, i.e., the accumulated CO₂ emissions, accrued cost of new renewable capacity and the installed renewable capacity. These characterize the state of the island system and also are the sources of inertia and memory. The flows, such as the investment rate and net monthly CO₂ emissions, are directly linked to their respective stocks and reflect the rates at which these stocks increase or decrease. In the modelling, planned renewable investments and existing renewable capacity are stocks which are determined endogenously. Our model is a long-timescale investment model and is not a short-term grid balancing model. We adopt a one-month time-step. As such in this work we are largely insulated from short-term issues of weather and renewables intermittency.

Figure 1 shows the three main feedback loops influencing renewable integration within the system. The green loop (balancing effect of locally influenced renewable target) captures the causal relationship between the amount of renewable capacity installed and the shortfall of the amount needed to reach the local renewables target. The purple loop (balancing effect of the globally-influenced CO₂ emissions target) shows the effects of the installed renewable capacity and planned investments of renewables on the global emissions targets of the island system. The red loop (reinforcing effect of local renewable learning curve experience) captures the extent of cost reductions that accrue from the experience of installing renewables. This loop captures the breakeven cost of renewable production capacity that is required for the system to be sustainable. These three loops are the key components underpinning the model’s structure, with their interactions being important for understanding the emerging characteristics of the system. In the work reported here we do not consider issues of long-term seasonal energy storage. This will be considered in future work focusing on the demand side. Shorter term (e.g. diurnal) storage is also omitted from this initial long-term investment model.

Additionally, social and economic impact plays a key role in the overall model, though at this stage these are secondary to the main feedback loops. The model crucially highlights a generic structure aggregating all renewable sources into a single entity. Later disaggregation will permit more accurate modelling, as the technological advancement with learning-curve cost reductions and profitability of the individual renewable sources can differ significantly. In later work we intend to focus on DSM and related social factors and to model this demand forecast as an endogenous component of the system. This will be pursued during further enhancements of the model.

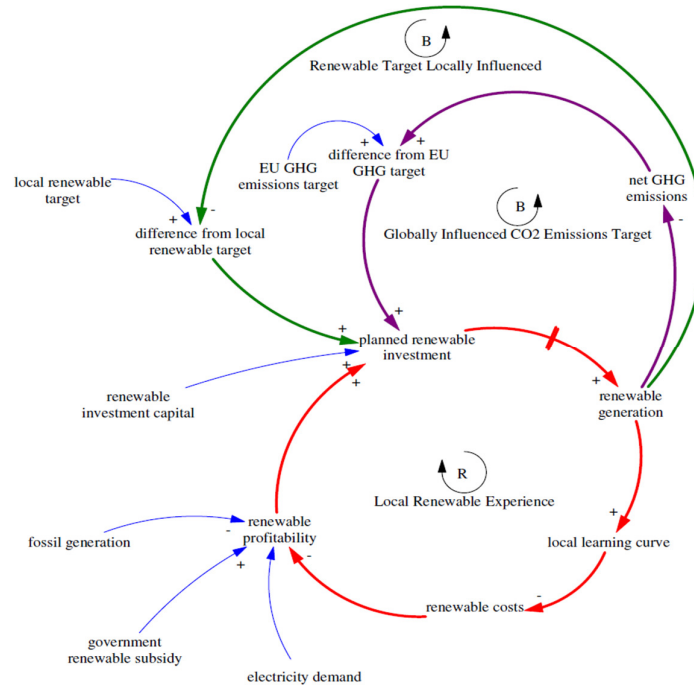


Figure 1 Overview of the key feedback structures related to renewable integration within the island electricity system

The simulation model is implemented using the Vensim software package. The model has been derived from the causal loop diagram (Figure 1), and includes the stock and flow variables that capture the key system structure. The important exogenous inputs are the local renewable targets, the CO₂ emissions targets, the electricity price and the electricity demand. In future versions of the model the electricity demand will be endogenous, but in this study our aim is to focus on renewable integration policies and cost reductions from installation experience. In this paper, the demand is assumed to be exogenous and storage is neglected.

To model cost reductions we follow [8] and write $C_{t+\Delta t} = C_t \left(\frac{X_{t+\Delta t}}{X_t} \right)^{-e}$, where C_i is the investment cost per MW at time t , X_t is the cumulative constructed capacity (including decommissions), and e is the learning curve parameter. The parameter $e = -\log_2(p)$, where p is the progress ratio with $0 \leq p \leq 1$. A progress ratio of 90% means that for each doubling of X_t there is a cost reduction of 10%. Following [16, p. 338], the model was tested with several realistic progress ratios. For the relationship of the progress ratio to the economic concept of learning-by-doing please see [8] and [16, p. 338].

Within the model (Figure 2) the key stocks are the planned renewable investments, the installed renewable capacity and the cost of new renewable capacity. The growth of planned investments in renewable capacity depends on the

investment rate, which, in turn, is affected by the total capacity required to meet (i) forecasted demand load; (ii) the financial expectations of investors; and (iii) the CO₂ and local renewable targets. To model the influence of targets, we use the approach given in [16], whereby R , the rate of adjustment of a variable S to a target S_* , is given by $R = (S_* - S)/T_A$, where T_A is the adjustment period.

Important dynamic components of the model are, for the monthly time step Δt :

- the rate of change of installed renewable capacity, $\Delta C_I/\Delta t = P_C - P_D$, where P_C is the rate of commencement of generation and P_D is the depreciation rate;
- the rate of change of planned renewable investments, $\Delta I_P/\Delta t = I - S_C$, where I is the investment rate and S_C is the rate of commencement of construction of new renewable capacity.

The investment rate I is a compound of several model variables:

$$I = \max((C_F - C_I)/T_I, (C_D - C_I)/T_I, R_R, R_E) + R_C$$

where C_F is the forecasted demand load; C_I is the installed renewable capacity; C_D is the financially desired renewable capacity; T_I is the capacity investment decision timeline; R_C is the rate of renewable capacity retirement; and R_R and R_E are, respectively, the rates of adjustment to the renewables and CO₂ emissions targets, as described above. The desired renewable capacity $C_D = A_R C_I$, where A_R is the investment attractiveness, which, following [17], we model as a piecewise linear function of profitability.

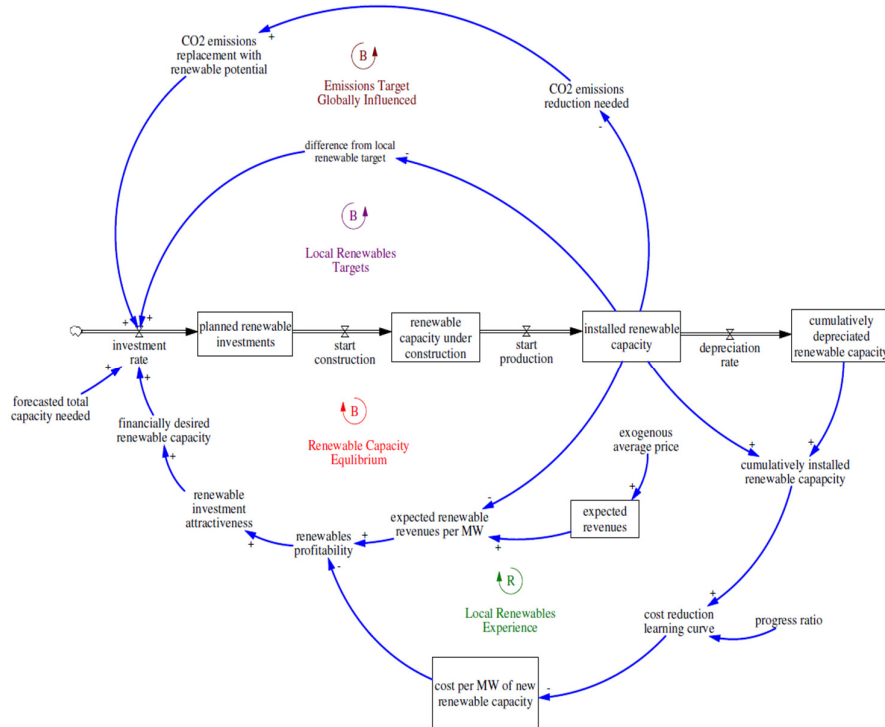


Figure 2 Simplified Stock and Flow Diagram of Simulation Model

Structural validation of the model is achieved by comparing model outputs with historical output data of the real system for the endogenous installed renewable capacity. Historical data for 2005-2014 of the key exogenous variables, such as the demand load and electricity prices, have been used to determine appropriate data extrapolations using the Vensim SMOOTH and FORECAST functions.

To gain some insights into the next 35 years of the system structure and variables, the model has been implemented, with a monthly time step, for the period 2005-2049. The investment decisions for the renewable integration within the system have been observed and insights given based on different renewable targets and CO₂ emissions policies (CO₂ avoidance trading certificates and a price for CO₂ emissions have been ignored). It is important to keep in mind that this renewable model is still to be integrated with a fossil-fuel capacity model [18] and a future demand-side-management model and therefore model outputs and insights are provisional.

4 Three Scenarios

Within the scope of this model we are able to see the effects of the renewable target and CO₂ emissions policy on the planned and installed renewable capacity within the system. The additional effects on the cost of renewable investments due to the cost-reduction from installation experience is also highlighted in the model. In all scenarios, the initial planned renewable investments, installed renewable capacity and cost of renewable investments are obtained from the historical data of São Miguel, for the initial time of January 2005. Model calibration time is given from January 2005 to December 2014, whilst the simulation period runs from 2015 up to 2049. Three different scenarios are used for evaluation, which vary according to the desired policies. The extrapolated input data for the exogenous peak demand of the system and the initial cost of renewable investments remain the same in all scenarios. The CO₂ emissions and renewable target policies are implemented as stated in Section 3, and by fitting the adjustment time and required goal to the desired policy. The three scenarios are:

Reference scenario: This scenario considers the “business as usual” case and represents the most likely outcome under a midterm goal of 50% reduced CO₂ emissions and 50% installed renewable capacity targets within the system by 2030.

Less-aggressive renewable scenario: This scenario features renewable policies that have a goal of 50% reduced CO₂ emissions and 50% installed renewable capacity targets within the system, by 2050.

Aggressive renewable scenario: This scenario represents the goal of 50% reduction in CO₂ emissions and 75% installed renewable capacity within the system by 2018.

5 Analysis

Figure 3 shows the observed trend for the planned renewable investments within the system. In all three scenarios, as outlined in Section 4, the initial state of the

model sets planned renewable investment at 9MW reflecting the reality of São Miguel in 2005. The monthly planned renewable investments peaks somewhere after 2011 for all scenarios but as expected the policy of 75% renewable by 2018 has a higher peak. After the peak the trend appears to be a steep decline into an exponential levelling off to zero around 2038 for all three scenarios. The similarity of the three scenarios is partly a consequence of assuming the same demand growth in each case. Future work will explore a range of scenario demands. Furthermore, it is expected renewable capacity will converge to meet the policy target as such, which is equivalent to archetypical s-shaped system dynamics behavior where such convergences might be with a system carrying capacity.

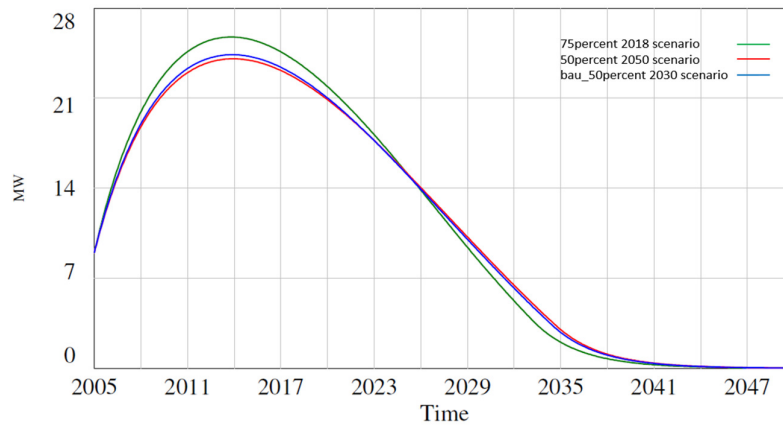


Figure 3 Planned Renewable Capacity Investments in 3 Scenarios

Following the planning stage, the installation and actual commissioning of installed renewable capacity can take 2-3 years. Figure 4 shows the amount of installed renewable capacity for all three scenarios, also compared to the real data of installed renewable capacity from 2005 to 2015 and the results of Ilić, in [19, Ch. 20]. All three of the scenarios reflect a similar amount of installed renewable capacity of about 39MW for 2015 in line with the real data. The calibration time of the model was short and there was an initial deviation from the real data, however the long term trajectory of both our simulated model and the real data tends to be correlated. Note, Ilić achieved similar results to the 80MW approximate value of installed capacity in 2028 using a stochastic dynamic programming method for long-term capacity planning. This provides some confidence in the validity of our work. The aggressive 2018 renewable policy has an installation peak that occurs faster and is higher than the 2030 50% policy and the 2050 50% policy. However the final capacity in 2050 does not differ by much and we think that this can be attributed also to the electricity demand growth on the island (the carrying capacity of the system).

Figure 5 highlights the cost reduction learning curve. This study used a 90% *progress ratio* resulting in a 10% cost reduction on the initial cost price in 2005 for every doubling of the renewable capacity within the system. The new renewable cost price for 2005 as given by [20] was used. By 2050, the cost of new renewable

capacity is shown to decrease by a small amount in all three scenarios indicating that the learning experience of the renewable element within the island is not very high. The corollary is that the learning-by-doing opportunity on such small islands is not very significant. Such learning effects are typically measured in terms of the cost reductions that can be expected from a doubling of installed capacity. The small size of the island system evidently restricts the potential for limitless growth and hence learning-by-doing.

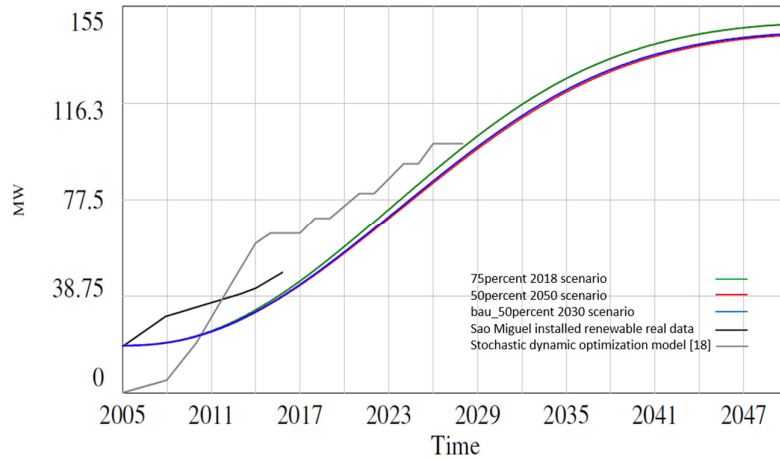


Figure 4 Installed renewable capacity. Our modelling (3 Scenarios), real world data and independent modelling [18].

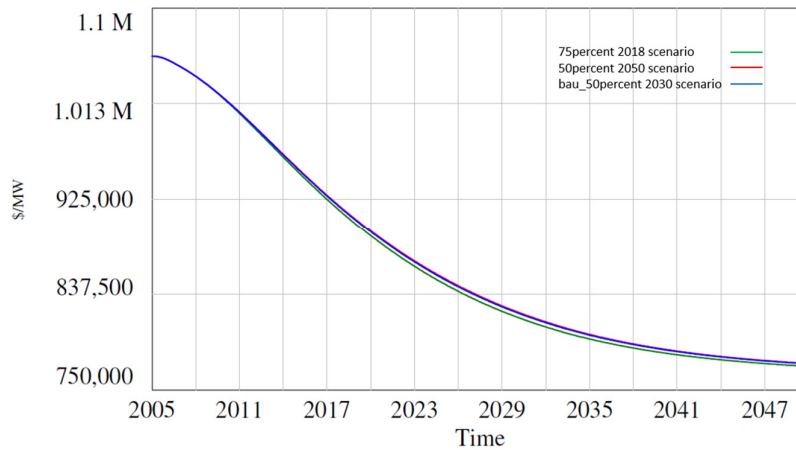


Figure 5 Costs per MW of capacity in 3 scenarios illustrating the effect of learning-by-doing

Figures 6 and 7 show the renewable capacity needs for CO₂ emissions replacement and how the deviation from the local renewable target influences the

three scenarios. In all cases, values are initially high then decrease in proportion to the aggressiveness of the associated policy. If stakeholders only considered these factors then there would be overly costly investment in the early years of the system. In Figure 6, both the reference “business as usual” and less aggressive policies achieved the local renewable targets by 2023. However, we see indications that the aggressive 75% 2018 policy appears to struggle. In that case the simulated model achieved its target by 2029. This can also be attributed to the carrying capacity of the system and the financial limitations attached to higher investments over a shorter time. Figure 7 implies that a higher amount of renewables are needed on a monthly basis for the aggressive renewable scenario in order to achieve the EU influenced CO₂ emissions goals. However, with less aggressive goals this target is achieved about 2 years later than the more aggressive policy goals. These observations emerge from this initial study restricted in scope and may evolve further as other factors are made endogenous to the model. One consideration that could greatly affect renewable generation is the effectiveness of diurnal and seasonal energy storage. We note the special role of hydro-power in this regard, which will be accounted for as different renewable types are disaggregated in future work.

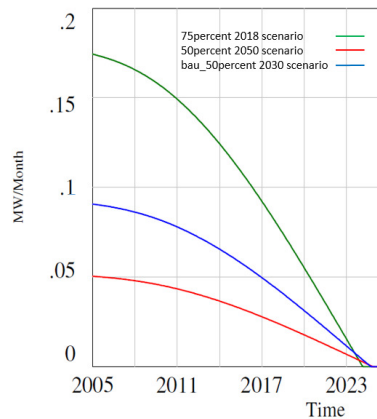


Figure 6 Convergence of modelled capacity with policy in 3 scenarios

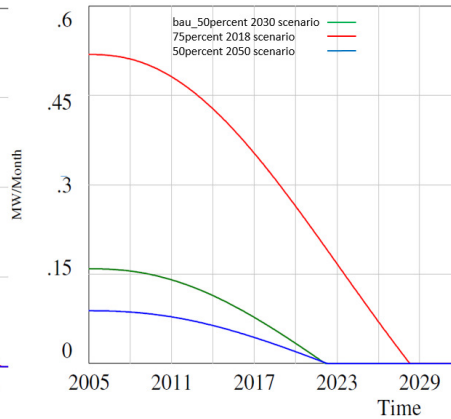


Figure 7 Convergence with CO₂ emissions target in 3 scenarios

6 Conclusions

This paper presents a system dynamics assessment of the renewable integration within the isolated island electricity system of São Miguel. Key components of the model highlight the cost reduction due to local learning from renewables and the type of renewable policy employed. Results and evaluations are starting to suggest that a sharp focus on achieving an aggressive renewable integration policy may lead to a boom and bust cycle of planning with periods of too much capacity. As shown in the results, in the long run, the required renewable targets will be achieved eventually, even with less aggressive renewable policies. This implies that possibly

the financial health of the system can be jeopardized due to higher investment costs needed over a short period of time. Island systems typically suffer from a weaker innovation landscape and from limited opportunities for learning-by-doing. These realities combined with the preliminary results reported here suggest that island systems policy-makers should consider adopting a carefully-paced approach and should probably avoid establishing a world-leading position in innovation. That said, the small scale of island systems can lend themselves to experimentation and world-class opportunities from learning-by-research [21]. All these initial ideas will be re-evaluated in the light of the more holistic work to come.

The insights distilled from the model show that there are benefits to be obtained from considering all of the key feedbacks including installation experience and the urgency of the renewable capacity targets as renewables are integrated. These seem to steer the long-term renewable investment outlooks and provide the gaps for the optimal generation mixes of the system. The model of the system uses many key variables such as demand forecast and electricity tariffs as exogenous inputs. Future work will include analysis of the demand forecast within the model with a view to modelling more aspects endogenously. Storage and renewable disaggregation will have a particular role to play in future work. We intend to consider shorter time-steps and in this way to model the daily/weekly short-term drivers of renewable dispatch within such island electricity systems. This will be based on the short-term availability and the relative cost of renewables compared to other electricity options within the island system. We further intend to include energy efficiency/demand side response and diurnal storage in our modelling.

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