A Low-Carbon Energy System Model Approach for Energy Planning in Madeira Island

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Abstract—Islands are extremely dependent on the importation of fossil fuels, mainly for the transportation sector and electricity production. The increase of the share of renewable energy generation in isolated electrical grids raises security and stability problems, as it introduces added variability in the consumption/supply load curves. Storage is one of the most advantageous possible solutions to address the deficit and variability in the consumption/supply in the electrical grid.

The scope of this work is to design a low carbon energy system for Madeira Island regarding the challenges of stability in isolated systems. The scenarios described were modelled with the vision to achieve 50% of renewable energies penetration in the electricity production system contributing to the reduction of fossil fuel consumption and carbon emissions according to EU targets.

For this reason, the study developed started by forecasting the energy demand from the reference scenario 2016 until 2030. The energy planning scenarios were created by modelling the existing electricity production system, achieving the calibration model, and comparing with the introduction of different system improvements in the supply that were divided in two scenarios.

In conclusion, a low carbon energy system plan was achieved with 54,8% of RES incorporation in the generation system and an incorporation of RES in PES of 46,5%.

Carbon dioxide emissions were reduced to 14,7% in the sensitivity analysis in comparison with the calibration model.

Keywords - energy planning; islands; renewable energy.

I. Introduction

The ability to produce energy, particularly in the form of electricity is, and has been, highly dependent on fossil fuels, such as coal, petroleum, and gas, which are known to be finite. Other aspects, such as geopolitical issues, natural disasters and severe climate can affect the functioning of power plants and thus the energy price volatility. Also associated with fossil fuels burning is the emission of greenhouse effect gases, particularly CO_2, that are linked to the ever growing problematic of global warming and its increasingly devastating consequences [4].

In several projected scenarios for the future of power generation in our planet, renewable energy sources (RES) play a role of growing importance, notably for addressing the two main problems of fossil fuel sources: their finite nature and acute greenhouse gas (GHG) emissions. However, the incorporation of RES (such as wind, hydro and solar) in the electricity mix of a system must be analyzed in detail due to their higher capital investment costs, higher levelized cost and variability. The higher costs when compared to fossil fuels result, generally, from three main factors: early-stage development of technologies, lack of economies of scale and low-capacity factors.

The increasing investment in electricity generation from RES is expected to enable a lowering of the costs of these technologies, due to reductions in capital and maintenance costs and increases in efficiency and lifetime. With the costs of technologies using fossil fuels expected to increase until 2030, some of the technologies using RES can achieve grid parity during this period. The problem of RES variability is particularly important for the introduction of non-dispatchable sources such as small hydro systems, wind and solar. Another disadvantage is that it is difficult to generate a similar quantity of electricity as those produced by traditional fossil fuel generators. For this reason, it is necessary to either produce more electricity, consume less or store any energy surplus for later use. Pumped hydro storage and batteries, in combination with RES, might offer a solution for both problems, storing energy surplus from the RES for later use. With energy storage, more power generated from variable sources can be introduced in the electrical grid without compromising security.

A. Modelling Energy Systems

Energy modelling tools are prepared to be applied to either the micro-scale or the macro-scale. The micro-scale models are usually detailed technology models for short-term simulation/optimization of components, technologies, buildings, or facilities, with high temporal resolution [9].

The macro-scale models are aggregated models for long-term planning of large energy systems or making economic/policy recommendations for countries or groups of countries [7].

In this work, the focus will be on energy systems planning and balancing models at a macro-scale.

In this case study the spatial resolution is a region, Madeira Island and the temporal resolution is the hour.

B. *Madeira Island Case Study*

Madeira Island is the larger of the two inhabited islands of the Madeira archipelago, situated in the Atlantic Ocean with a total population of around 250 000 inhabitants.
Island electricity systems are characterized by a significantly higher generation margin. As their systems are not interconnected to import electricity in case of demand surges and generator faults, operators have to ensure security of the system at any given moment by creating high generation margins. Another size-related challenge for the system operators is the lack of economies of scale.
For this reason, Islands are isolated systems unless they are sufficiently near the continent to be connected by cables along the sea bottom.
Madeira has an isolated electricity system although possibilities of interconnections are being further studied.

II. METHODOLOGY

The main purpose of this work is to estimate an energy plan regarding a sustainable energy system for Madeira Island.
The methodology applied is divided in four parts that include:

1. Energy Demand and forecast
2. Calibration model and validation
3. Modelling scenarios for sustainable energy systems
4. Sensitivity Analysis

The preparation of a regional energy system solution constitutes a planning instrument, that defines a clear strategy of the adopted energy policy, as well as a support instrument for the implementation of foreseen measures.
For this reason, EnergyPLAN modelling tool was required in order to comply with the objectives and targets defined in the established timeframe.

A. *Goals*

- Increase in 50% the use of renewable energy resources in electricity production until 2030.
- Reduce CO_2 emissions by 20% in 2030 in comparison with 2016.

B. *Energy Planning*

In sequence to the goals that has been presented, the actual situation and future perspectives for socio-economic development and growth of the energy sector require a sustainable energy policy based on efficiency and valorization of local resources, as described in the objectives set by the European Union on Energy and Climate.
For this reason, the strategy for the Energy Policy is the following:

- Increase integration of renewable resources in the production mix by studying the potential incrementation of solar photovoltaic panels for electricity production, increase hydro power energy supply, wind energy and biomass with waste for incineration and electricity generation.
- Energy storage strategies to reduce impact of the RES variability, such as batteries and hydro pump storage.

III. ENERGY DEMAND

According to the real electricity consumption and after analyzing the historical data it was estimated the evolution of energy demand in Madeira Island until 2030.
The extrapolation takes in consideration 3 following cases:

A. *Minimum Consumption (Cmin)*

The minimum scenario describes less impact in energy demand to compare with the other scenarios, regarding for instance the fluctuation of macro-economic parameters such as population which is predicted to decrease in the near future until 2050.

B. *Inferior Consumption (Cinf)*

The inferior consumption scenario describes the evolution in the demand for electricity if the total consumption evolve at an average rate of 0,5% on the energy demand in Madeira Island between the period 2015-2030.

C. *Base Consumption (Cbase)*

This scenario describes the evolution in the demand for electricity assuming that the total consumption evolve at an average rate of 1,5% on the energy demand in the Madeira Island between the period 2015-2030. Losses in distribution and transportation considered were 8,7% of total electricity production emitted [17].
In 2016, total electricity production emitted to the SEPM was 829,67 GWh, considering the pumping of 0,72 GWh, contributing to 757 GWh of electricity consumption in the reference year (2016) [17]. The energy demand forecast on each case is represented in Fig. 1.

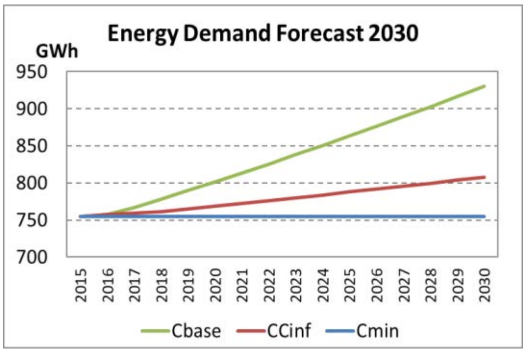

Figure 1. Energy Demand Forecast until 2030.

The next step was the calculation of the electricity production emitted.

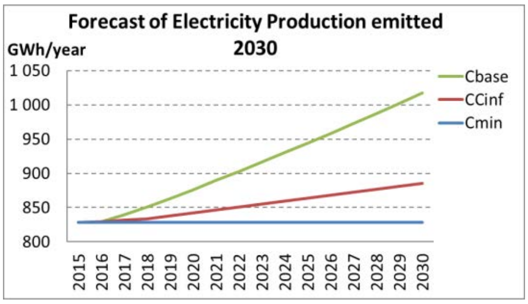

Figure 2. Forecast of Electricity emitted until 2030.

IV. CALIBRATION MODEL AND VALIDATION

It is important to notice that the calibration model (reference 2016) and in both scenarios studied it was considered an energy demand according to the case Cinf described before. In other section it was studied a demand sensitivity analysis.

In the first place, all hourly distributions were updated after previous data analysis into the program, then the electricity demand was introduced and the supply. The incineration of the Municipal solid waste was calculated considering that 80% of total waste is incinerated (74 476 ton) producing 35 GWh (473kWh /ton). In this case at least 22343 ton of biomass (30%) could be incinerated increasing the overall capacity and efficiency of the process. Regarding the efficiency of 0,229 the total input of waste is 154,7 GWh/year.

The 10 Hydro plants were simulated taking in consideration the pumping, turbine and storage from Socorridos. The pumping and storage was assessed in the balance and storage tab, CO_2 emission factors for the calculation of the content of carbon in the fuels and fuels prices were calculated. Results obtained in the technical strategy are shown in TABLE I.

TABLE I. CALIBRATION OF THE MODEL

Simulation	Baseline 2016	Calibration Model
Electricity Demand (GWh)	828,95	828,95
Fossil Fuel Power Plant (GWh)	456,16	455,52
NG Power Plant (GWh)	120,77	120,77
Hydro Power (GWh)	104,84	104,84
Wind (GWh)	82,48	82,47
Waste (GWh)	35,57	35,57
Biomass (GWh)	-	-
PV (GWh)	29,85	29,85
Pumping (GWh)	0,72	0,27
Turbine(GWh)		0,21

Total carbon dioxide emissions shown in TABLE II differ in 19% from the model calibration; this may be due to the emission factors from each fuel in order to measure the content of carbon.

TABLE II. RESULTS AND INDICATORS

Results	Baseline 2016	Calibration Model
CO_2-emission (total)	366,89	453,90
RES share of PES	26,1	23,4
RES share of elec. Prod.	30,5	30,5
RES electricity prod.	252,75	252,72

V. ENERGY SYSTEM MODEL RESULTS

To achieve the targets set and accomplish the energy policy plan, actions were studied to improve energy efficiency, encourage the use of renewable energy as alternatives for less pollutant energy in comparison to petroleum-based products and reduce carbon dioxide emissions.

The possibilities were studied through the preparation of scenarios, testing numerous options and simulating the interactions between the various cases, to determine and ensure as best possible the results to be achieved, in view of the objectives and targets for until 2030.

The expected results with the implementation of the energy policy plan, in terms of energy savings, renewable energy increase and reduction of carbon dioxide emissions, are presented in the following table.

The energy policy plan was designed in the domain of secondary energy production, referring essentially to electricity production.

Two scenarios were created regarding the application of the energy policy plan and two sensitivity analyses were performed in order to study the sensitivity of demand. Results are presented in TABLE III.

Scenario 1 and Scenario 2 differ in the storage system regarding the simulation of batteries or pumping storage for reversible Hydroelectric Plant.

TABLE III. RESULTS

Simulation	Scenario 1	Scenario 2
Electricity Demand (GWh)	884,53	884,53
Hydro Power (GWh)	238,09	238,09
Wind (GWh)	115,37	115,37
Waste (GWh)	35,57	35,57
Biomass (GWh)	28,63	28,63
PV (GWh)	128,47	128,47
Storage System	10MW Batteries, 2,5MWh (15 min autonomy) (BESS)	11,1MW pump hydro storage , eff. 0,85 Turbine 8MW, eff. 0,9
CO_2 Price	20,32	20,32
Interest rate	0,5	0,5

Both scenarios 1 and 2 were studied regarding 2030 prices and considering the Demand forecast Cinf. However, oil prices are driven by global market balances that are mainly influenced by external factors.

Scenario 1 in 2030 consists on the increasing penetration of renewable resources for the electricity production.

In this situation a battery for energy storage is simulated when there is a production surplus.

a) Achievements

The energy policy plan was applied in the model created and an increase in RES primary energy sources was achieved.

Regarding Madeira Island intermittent renewable resource, there are 5 principal pillars for better stability and sustainability of the energy system:

- Introduction of natural gas in thermal power generation.
- Increase water retention and water storage capacity and the power installed of hydroelectric plants and reversible hydroelectric plants.
- Installation of wind farms and micro-wind turbines in micro and mini production regimes.
- Installation of solar photovoltaic parks and solar photovoltaic kits in micro and mini production regimes.
- Study of energy storage strategies such as batteries and pumping storage in reversible hydroelectric plants.

b) Results

A battery of tests was developed in EnergyPLAN in order to study the impact of the parameters in the energy system stability and sustainability. The influence of the volatility of carbon dioxide emission prices and their emission factors (content in fossil fuel), fuel oil prices, natural gas prices and gasoil prices will have a highly impact in modeling strategies because simulations will converge in guidance of these metrics.

For this reason, data were calculated by analyzing the historical data and extrapolating the equation for 2030 according to 2030 market trends. Scenarios with a higher interest rate such as 7% will increase costs.

A comparative analysis of all the scenarios studied and their variation in the decision-making is described in Fig. 3.

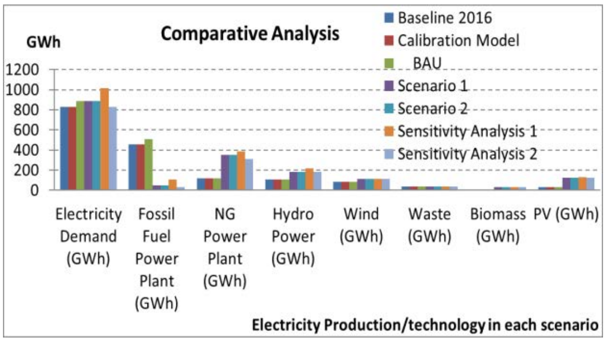

Figure 3. Comparative analysis of electricity production scenarios and the sensitivity analysis.

Analyzing the results obtained in Fig. 3 it was accomplish on both 2030 Scenarios 54,8% of RES incorporated in the electricity production.

In this case the RES share of primary energy source was 46,5% in Scenario 1 and 2 (46,4%) in 2030.

Carbon dioxide emissions were reduced 14,7% in the Sensitivity Analysis 2 in comparison with the CO_2 obtained from calibration model.

However, total carbon dioxide reduction of 8,7% was achieved in Scenario 1 in comparison with the calibration model in 2016, one possible explanation could be the fact that in this scenario 1 the consumption of fuel oil decreased.

It is important to notice that Scenario 1 2030 predicts the increase capacity of hydroelectric plants and pumping storage (61,1MW), photovoltaic panels and wind turbines regarding the fact that two Thermal Power Plants will end operations in 2023 and in 2025 respectively.

Furthermore, in 2016 there was total 93095 ton of municipal solid waste (MSW), from which 80% is incinerated producing 473 kWh/ t with an efficiency of 0,229.

According to the European Green Deal and following the vision to reconvert the waste produced in time, the capacity of the incineration could be raised and more electricity could be produced.

Furthermore, it is important to notice that BAU Scenario in Fig. 3 is the worst scenario created.

This BAU scenario traduced the level of the energy system until 2030 regarding the same characteristics as in 2016 (no further developments in capacities, renewable energy and storage) but in this case with no energy policy plan.

In this situation, in BAU Scenario with no energy policy plan, carbon dioxide emissions will increase 35,2 % in comparison to 2016 baseline.

The assessment of the data obtained during the predictions demonstrates the advantages of Scenarios 1 and 2 in diminishing fossil fuel consumption and the significant 20% of Hydro Power and 10% increase in PV including 3% of biomass. The distinction is Scenarios 1 and 2 is that in 1 a 10MW with 2,5MWh (15 min of autonomy) battery is installed and in Scenario 2 pumping storage for reversible Hydroelectric Plant strategy is implemented with the clear reduction e Thermal Power Plant.

Figure 4. Annual Fuel Consumption.

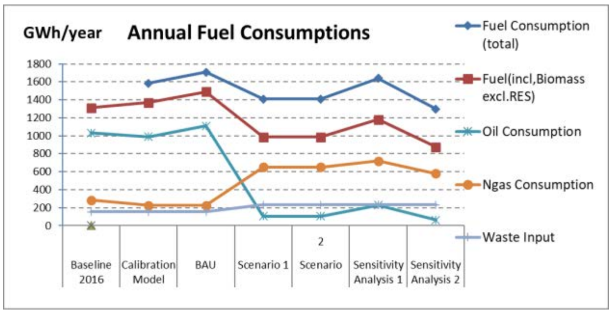

Fig. 4 demonstrate a clear reduction on fuel oil consumption in Scenarios 1 and 2 and then a significant reduction of the annual fuel consumption in the sensitivity analysis 2.

Total fuel consumption was reduced in 11% in Scenario 1.

An increase in natural gas consumption is also noticeable as expected.

Furthermore, it was selected, calculated and developed a spyder diagram for the analysis of 4 indicators in order to compare de good fitting solution regarding the scenarios evaluated.

Comparative analysis in Fig. 5 indicate that Scenario 1 is the most balanced solutions. However, the profile will depend in the demand requirement

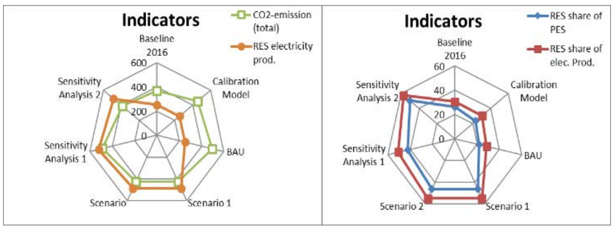

Figure 5. Indicators of CO_2 emissions, RES and PES in total electricity production.

VI. SENSITIVITY ANALYSIS

The previous scenarios were calculated considering the energy Demand Cinf, however regarding the projections of macro-economic variables such as demography with the trend to decrease and GDP it was crucial to study the behavior of the model when these parameters varies in order to evaluate the sensitivity of demand.

The Sensitivity Analysis 1 is related with the results obtained in 2030, considering a demand Cbase. In this case the model is able to balance this demand increasing according to the priorities defined in early sections.
The Sensitivity Analysis 2 is related with the sensitivity of the demand to fall to Cmin 754,35 GWh with a total production emitted of 828,12 GWh.
In the Sensitive Analysis 1 the demand increased to Cbase and total production emitted was 1016,92 GWh. The installation of batteries is considerad in both analysis and a total reduction to 10% of fuel oil is achieved reducing imports and consumption.
Another key factor was the increase in Hydro Power to 21% and 22% in the Sensibility analysis 2.
In addition, in this situation it is noticeable the increase in natural gas consumption in 38%.
This could be also related to the fact that the importation of natural gas from the USA could increase and this market fluctuation would surge a reduction in natural gas price and in contrast fuel oil prices will increase.
TABLE IV represents the summary of the variables for the sensitivity analysis.

TABLE IV. CALIBRATION OF THE MODEL

Demand 2030	Sensitivity Analysis 2 Cmin	Cinf	Sensitivity Analysis 1 Cbase
Electricity Consumption (GWh)	754,35	807,71	930,14
Production emitted (GWh)	828,12	885,25	1016,92

VII. DISCUSSION AND CONCLUSION

The scope of the work was to design an Energy Policy Plan for Madeira Island energy system regarding the challenges of stability in isolated systems.
In the first section a 2016 reference year was selected in order to calibrate de model resulting in a deviation of 4,7%.
In the second section two scenarios were described, the first scenario aims to reduce the electricity production from Thermal Power Plant in to 100MW, in this scenario it is expected that two thermal power plants end operation in 2022 and 2025 respectively and for this reason an increase in renewable resources is crucial to achieve demand.
This scenario also includes a higher capacity of hydroelectric plants (total 238,09 GWh), photovoltaic panels, two wind parks with total emitting 115,4 GWh. In addition it is calculated the necessary capacity for integrate more biomass in the waste incineration process improving calorific value of the moisture (30% to 50%).
In order to balance these situations, predictions were made, and batteries were the solution of this scenario to compensate a supply surplus. In this case, for instance in photovoltaic panels a total 128,47 GWh/year emission with batteries could be 137,10 (coefficient of 0.98).
Energy policy was achieved with RES incorporation in the generation system of 54,8% and an incorporation of RES in PES of 46,5%.
The second scenario contributes to an excess in renewable resources results were pumping storage for reversible hydroelectric is increased .
For this reason, prices in 2016 and 2030 were identified, calculated and and projected.
Regarding the volatility of fossil fuel prices and carbon dioxide emissions price new scenarios were performed in Technical and Marker optimization strategy with different interest rate.
Sensitivity analysis of demand was studied in order to design in regional scale 3 cases and evaluate results.
Carbon dioxide emissions were reduced to 14,7% in the Sensitivity Analysis 2 in comparison with the CO_2 obtained from calibration model in accordance to targets and energy policy.
In order to counteract systemic risks most islands operate with generation margins of around 30-40% compared to 15-20% in mainland highly interconnected grid systems. This high level of generation reserve causes extra costs but improves the reliability of electricity supplies.
For island energy operators, one of the main challenges is to achieve the switch to an environmentally sustainable energy production while ensuring a reliable, safe and economically viable production of electricity.
The variability of some RES technologies lead to new system stability threats and the need for balancing. Islands experience even more challenges in their move towards a higher integration of RES than the European continent since they cannot depend on the ‘smoothing out’ effect of a large balancing area.
Optimizing interconnectivity over geographically disperse RES generating units, in order to take the best advantage of the smoothing effect, is a possible way to reduce the total energy storage capacity needed. The total storage capacity needed is, as so, a function of the net variation ratio of the RES. Wind generation net variation ratios between 10% and 30% in 2050 correspond to needed storage capacities ranging from 40 GW to 100 GW, which means that an additional capacity of 7 to 67 GW would be required to mitigate wind power net variations.
In conclusion, the more RES installed capacity added, and the more net variation introduced to the grid, equates an increase in the required energy storage capacity.
Comparison between different energy storage technologies and their features show in the literature that pumped-hydro stands out as being the most efficient for intermittency balancing with a high capacity. It is also the technology with the largest discharge time scale, meaning it can perform for longer, assuring generation and grid security.
In conclusion, the use of energy storage systems is particularly important when planning systems with high penetrations of RES, since their variability and intermittency can lead to mismatches between electricity supply and demand as well as grid operation issues. The planning of systems with high penetrations of RES should therefore consider the option of using energy storage systems and new ventures as batteries or hydrogen to increase energy efficiency, security and stability in Madeira Island energy system.

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