Design optimisation for a hybrid renewable microgrid

Application to the case of Faial Island, Azores Archipelago

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ABSTRACT

The integration of intermittent renewable energy sources (RES) represents a great challenge for any energy system. In particular, islanded microgrids with a high penetration of renewables experience a strong need for technologies that allow to match demand and production at any moment, which are still largely represented by fossil fuel generators.

This work aims at proposing an optimised design for the energy system of Faial, an island in the Açores archipelago, featuring the highest possible renewable energy penetration which can be obtained respecting the technological and financial feasibility constraints. To this purpose, a model has been developed, using weather and electric demand measured data to combine and size optimally the components of a hybrid energy system featuring wind, photovoltaic, geothermal and diesel generators, as well as battery energy storage systems (BESS). The model can be varied in its contraints to fit at best the multi-objective nature of the problem, where the conflicting objectives are the Net Present Value (NPV) of the system design, its Renewable Energy Fraction (REF) and the Energy Index of Reliability (EIR), defined as the percentage of demanded energy that is matched by the generators.

Once a set of possible optimal design has ben determined, a system design featuring 5504 kW of geothermal installed power and 6208 kWh of BESS capacity, together with the already present thermal generators and 4250 kW of wind turbines, has been analysed more in detail. Such system design, totalising an initial investment of 28.85 M€, has a NPV of only 43’000€ when compared to the current system configuration, which anyway can rise to roughly 6 M€ with an adjustment of the electricity retail price of around 10 €/MWh. Monte Carlo simulations with synthetic time series have been performed to investigate the impact on the project of the variability in wind speed and in energy demand, highlighting the robustness of the selected design.

Keywords: hybrid renewable microgrid; optimisation; Monte Carlo simulations; stochastic processes; synthetic time series; Azores.

INTRODUCTION

Micrograds are small-scale power networks independent from the main large energy transmission systems, sometimes interconnectable, and sometimes completely separated because of geographical constraints. The concept of microgrid is becoming more and more widespread, not only in small islands or remote communities as highlighted in [1] and [2], but also in modular configurations inside large grids, allowing different districts and facilities to be independent from each other in case of need and to work independently with a higher resilience in the event of network outages [3]. When operating in island mode, microgrids are charactrised by high fuel costs, as the need for network stability forces a low penetration of RES. On the other hand, RES provide new solutions against the progressive inefficiency and high expenses of conventional energy systems in island regions.

Just in Europe there are about 300 islands (6% of the Union Territory) with 14 million inhabitants, more than the whole population of some member states such as Portugal [4]. In many cases, such islands are not connected to the mainland's energy network, and rely on their own microgrid, offering a good terrain for experimenting new technologies and concepts for cleaner energy solutions.

EDA, the utility company in the Azores, has a strategic plan which involves investing 130 M€ in years 2018-2022 [5] only for renewables and storage systems, such as new pumped hydro systems in São Miguel and Terceira, an innovative hybrid system with battery storage in Graciosa, and a 600 kW photovoltaic plant in Santa Maria. This work focuses on analysing the potential role of Faial in this framework, studying the impact and the challenges of developing a project for a hybrid renewable microgrid.

LITERATURE REVIEW

In the past years, the scientific community has dedicated a great amount of effort and work to the topic of microgrid modeling and optimisation, investigating also the future potential and applications of this energy system paradigm. While [1] and [2] highlight its potential for rural electrification, [3] illustrates how the microgrid concept can be applied in a modular way to allow large scale deployment of distributed RES in conventional grids, in the limits of RES integration investigated by [4]. To assess the long-term performance of a hybrid system, [6] proposes a versatile probabilistic approach to combine with Monte Carlo simulation.

As for the simulation models, [7] modifies a Unit Commitmend and Economic Dispatch (UC+ED) model to determine the optimal BESS size to provide spinning reserve and to reduce the load on thermal generators in Terceira, similarly to what is proposed in this work. Recently several hybrid renewable microgrid optimization techniques have been developed, including Artificial Intelligence, Genetic Algorithms (GA), Fuzzy Logic and Artificial Neural Networks as illustrated in [8]. Some of these methaeuristic methods, specifically GA and PSO, have been succesfully applied to the a case study in the Azores in [9]; nevertheless, this work used probabilistic methods to solve the UD problem, as it is a simple and efficient approach as demonstrated in [10] and [11].

Several other researches have studied innovative energy solutions in the Azores: [7] and [12] focused on BESS integration, while [13] quantified the benefits of demand-response optimisation. [14] analysed the impact of the introduction of electric vehicles as a means of storage, while [15] assessed the benefits of a Water Pumped Storage System (WPSS).

METHODOLOGY

The hybrid energy system (HES) in this work is a network of several components, as shown in Figure 1. The renewable part of the system is composed by wind turbines, a geothermal power plant and photovoltaic arrays. Diesel engines provide spinning reserve and fulfil the load-following role in the system, together with the energy storage system. In the Faial case study this have been assumed to be Li-Ion batteries for their quick response, but in general this model does not put any constraints against other sources of storage such as flywheels.

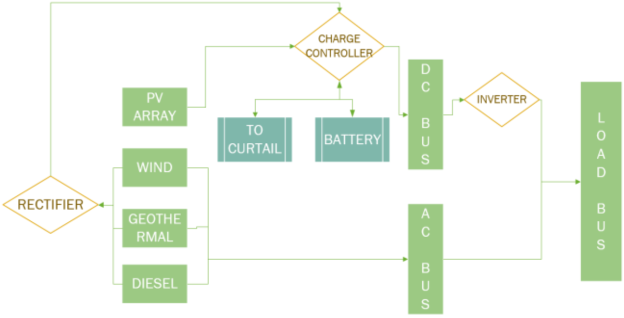

FIGURE 1 – PROPOSED SYSTEM CONFIGURATION

The system has an AC bus to which wind, geothermal and diesel generators are connected, and interfaced directly with the grid and the loads. At the same time, a rectifier allows the possible power production excess to be stored in the battery, through a charge controller, or to be curtailed. The PV arrays are connected directly to the charge controller, which manages the power flows between PV array and battery and the inverter which interfaces the DC bus with the grid.

Since five wind turbines are already installed in the island, the assumption has been made that the model used the same turbine model, Vestas V52/850, to calculate the power production also for potentially new turbines. The energy produced by PV panels is proportional to the solar irradiation, and has been calculated using the HDKR model [16].

The energy generated from renewable sources in a time step is then defined as:

$$E_{RES} = E_{wind} + E_{PV} + E_{geo} \qquad (1)$$

The simulation model, written in MatLab, receives inputs from three *.m* files, containing respectively the hourly demand, the hourly average wind speed (HAWS) and the specific electric production in W/m^2 of PV panels installed. After these input data have been loaded, the RES power generation for each time step is calculated with equation (1).

Then the required spinning reserve (SR) is calculated according to its definition. In the case study of Faial SR is related to the wind speed, as common practice by EDA [9], and its definition is reported in equation (22). If the sum of the energy produced by RES and SR exceeds the load, the excess is stored in battery or, if the battery is full, part of the RES generation is curtailed. Otherwise, if additional power is still needed, a Unit Commitment (*UC*) model is called from a separate function to determine the optimal dispatch and power output of the thermal engines to match the remaining load, and the respective cost.

This strategy is described by the following equations, starting with the calculation of the energy flow managed by the charge controller between the RES array and the battery:

$$E_{to}^{BESS} = (E_{RES} + E_{SR}) - E_{load} \qquad (2)$$

Where E_{to}^{BESS} is the energy sent or requested from the battery, depending if such value is greater or smaller than zero respectively. At this point, the energy theoretically present inside the battery E_{into}^{BESS} amounts to:

$$E_{into}^{BESS} = C_B \cdot SoC_{bop} + E_{to}^{BESS} \cdot \eta_{BESS} \qquad (3)$$

Where C_B is the capacity of the battery, which coincides with the decision variable x_4, SoC_{bop} is the state of charge of the battery at the beginning of the period, expressed as a value from 0 to 1, and η_{BESS} is the efficiency of charge and discharge of the battery. So far, E_{into}^{BESS} does not take into account the limits of minimum and maximum energy that can be stored, which are imposed by the definition of the state of charge at the end of the time step, SoC_{eop}:

$$SoC_{eop} = \begin{cases} 1 & if \dfrac{E_{into}^{BESS}}{C_B} > 1 \\ \dfrac{E_{into}^{BESS}}{C_B} & if\ SoC_{min} \le \dfrac{E_{into}^{BESS}}{C_B} \le 1 \\ SoC_{min} & if\ \dfrac{E_{into}^{BESS}}{C_B} < SoC_{min} \end{cases} \tag{4}$$

Equation (4) encompasses all the possible behaviours of the battery, charging or discharging inside its operational range, or reaching its upper or lower limit of charge, respectively 1 and SoC_{min}. In case the battery is full, part of the energy sent to the battery must be dissipated; the energy that the charge controller curtails has been defined as:

$$E_{curt} = \begin{cases} E_{into}^{BESS} - C_B & if\ SoC_{eop} = 1 \\ 0 & else \end{cases} \tag{5}$$

On the other hand, the amount of energy discharged by the battery, E_{disch}^{BESS}, is:

$$E_{disch}^{BESS} = \begin{cases} \left(SoC_{bop} - SoC_{min}\right) \cdot C_B \cdot \eta_{BESS} & if\ \dfrac{E_{into}^{BESS}}{C_B} < SoC_{min} \\ \max(-E_{to}^{BESS} \cdot \eta_{BESS}\ ; 0) & else \end{cases} \tag{6}$$

Finally, the remaining load to be supplied by the thermal generators, $E_{thermal}$, is computed:

$$E_{thermal} = E_{load} - (E_{RES} + E_{SR} + E_{disch}^{BESS}) \tag{7}$$

The value of $E_{thermal}$ is sent to the UC function to determine whether it is feasible to provide by the thermal generators, and with which optimal dispatch of the gensets.

In case the thermal generators are used below their minimum load point, the generation is forced to increas up to that point, and the behaviour of the battery is recalculated:

$$\begin{aligned} if\ E_{SR} + E_{thermal} < C_{min}^{therm} \rightarrow E_{thermal} \\ = C_{min}^{therm} - E_{SR} \end{aligned} \tag{8}$$

$$E_{to}^{BESS} = (E_{RES} + E_{SR} + E_{thermal}) - E_{load} \tag{9}$$

At the same time, the sum of SR and the rest of thermal generation must be lower or equal to the installed capacity of the generators C_{therm}, 19100 kW in the case of Faial:

$$\begin{aligned} if\ E_{SR} + E_{thermal} > C_{max}^{therm} \rightarrow \\ E_{thermal} = C_{max}^{therm} - E_{SR} \end{aligned} \tag{10}$$

At the end of this, the time step is solved and the simulation passes to the next one. The process is repeated for every hour of the year; at the end, *objfun* calculates the total energy produced by the generators of each type, and computes the Renewable Energy Fraction (REF_{min}) and the Energy Index of Reliability (EIR_{min}) of the system. These parametres are defined as follows:

$$REF = \frac{\sum E_{RES} - \sum E_{curt}}{\sum E_{load}} \tag{11}$$

$$EIR = 1 - \frac{EENS}{\sum E_{load}} \tag{12}$$

Where E_{RES}, E_{curt} and E_{load} are respectively the energy produced from RES, the energy curtailed and the energy demand at each hourly time step, and $EENS$ is the total Expected Energy Not Supplied at the end of the period considered:

$$EENS = \sum_{8760} \left[E_{load} - \begin{pmatrix} E_{RES} + E_{SR} + \\ +E_{disch} + E_{thermal} \end{pmatrix} \right] \tag{13}$$

Finally, the NPV of the system is calculated according to equation (14):

$$\begin{aligned} NPV_{project} = \left(\sum_{y=1}^{20} \frac{FCFF}{(1 + WACC)^y} \right) + rv \cdot CAPEX \\ \cdot CPI_{20} \cdot \frac{1 - tax\ rate}{(1 + WACC)^{20}} \end{aligned} \tag{14}$$

Where FFCF are the free cash flows to firm, WACC is the weighted Average Cost of Capital, rv is the the residual value of the project discounted with the inflation rate (Consumer Price

Index CPI at year 20), and CAPEX are the capital expenditures.

The NPV represents the actualised value of all the net income cash flows generated by the project, plus the residual value of the installations at the end of their nominal 20 years lifetime.

The optimisation model has been developed in MatLab, based on the *fmincon* engine for constrained objective function minimisation. The decision variables are the installed capacities of the RES generators in kW, as well as the storage capacity in kWh, are also referred to as follows:

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \begin{pmatrix} wind\ [kW] \\ PV\ [kW] \\ geothermal\ [kW] \\ storage\ [kWh] \end{pmatrix} \tag{15}$$

The objective function to maximise is the compared Net Present Value (NPV) of the system over 20 years, which is simply the difference between the NPV of the configuration under study and the NPV of the current configuration of the system.

To cope with the multi-objective nature of the problem, the secondary objectives have been introduced as linear and non-linear constraints. In particular, lower (LB) and upper bounds (UB) to the decision variables can be customised, and minimum values for the Renewable Energy Fraction (REF_{min}) and the Energy Index of Reliability (EIR_{min}) can be imposed.

The constraints can be described as:

$$\begin{cases} LB \leq x \leq UB \\ REF \geq REF_{min} \\ EIR \geq EIR_{min} \end{cases} \tag{16}$$

For computational power limitations, the model operates at hourly time steps for one year. The environment conditions and energy production are assumed to remain constant for the rest of the system's lifetime.

The optimisation algorithm starts from an initial guess of the decision variables, x_0, and iterates on it towards an optimal solution until the steps in the values of the variables and of the objective function become too small to be significant. The non-linear constraints of REF_{min} and EIR_{min} are defined in a separate function, *nonlincon*, that receives the values of the constrained variables which are calculated by *objfun* at every iteration. The objective function *objfun* represents the simulation model: it contains the energy model and the calls to the UC model and the financial model, and can be run independently from the optimisation algorithm in case only a single scenario has to be simulated.

Finally, the values of the decision variables in the iteration, the total yearly cost for thermal engines, the energy production and the CO_2 generation are passed to another function which calculates in detail the NPV of the project. When the decision variables converge to an optimal result, an Excel sheet is printed with the hourly breakdown of the energy balance, the values of the decision variables, the NPV of the project compared with the current system, the EENS, EIR and REF.

THE FAIAL CASE STUDY

The island of Faial, belonging to the central group of the Açores, is the third most populous island in the archipelago after São Miguel and Terceira. In its 173 km^2, Faial was home to 14.759 inhabitants at the end of 2016 [17], around 6% of the total Açores population. Its energy system is characterised by mainly domestic and commercial users, on a scale which is small enough not to require a high voltage (HV) transport grid, so that only a distribution grid is present.

Electricity generators in the islands include the 320 kW Varadouro hydropower plant, the 4.25 MW Salão wind park, and a set of six thermal generators, as summarised in Table 1, which are fueled with heavy fuel oil (HFO) and can operate at a technical minimum of 50%.

TABLE 1 – SUMMARY OF FUEL GENERATORS IN FAIAL

NAME	MODEL	POWER [kW] (PF = 0.8)
G3	Sulzer 6ZL 40/48	3000
G4	Sulzer 6ZL 40/48	3000
G5	Krupp MAK 6M4 53C	2000
G6	Caterpillar/MAK 8C M32C	3705
G7	Caterpillar/MAK 8C M32C	3705
G8	Caterpillar/MAK 8C M32C	3697
TOTAL		**19107**

From the data obtained by EDA's archives, it is possible to observe that the production of the hydro plant is highly unreliable and, when present, is a negligible share of the yearly production in the island. For this reasons, for simplicity hydropower has been excluded from the model presented in this work [18].

INPUT DATA AND SYNTHETIC TIME SERIES GENERATION

The data for electricity demand have been made available by EDA for only four days, precisely the 20th day of January, April, July and October of 2017, with intervals of 30 minutes. Load curves for every other day has been generated with Monte Carlo sampling: every needed hourly demand value of any day of the year has been expressed as a normal probability distribution. As mean, the distribution uses the mean of the load values at the same hour of the two nearest days between the ones provided by EDA. As standard deviation, their semidifference of the same values was used. As an example, indicating with L_{may8}^{13} the load in kW between 13h and 14h on the 8th of May, and with μ and σ the mean and standard deviation of its probability function:

$$\mu_{may8}^{13} = \frac{L_{apr20}^{13} + L_{jul20}^{13}}{2} \tag{17}$$

$$\sigma_{may8}^{13} = \frac{\left|L_{apr20}^{13} - L_{jul20}^{13}\right|}{2} \tag{18}$$

In this way, infinite random yearly demand curves with hourly values can be generated, respecting the statistical trends that link them with realistic scenarios, while at the same time allowing the presence of a few outliers. Such values represent situations that are highly unlikely to happen but not impossible, and are therefore useful to test the resilience and the ability of the energy system to deal with those situations.

Data regarding wind speed and direction have been made available by EDA for the year 2017 only, at intervals of 10 minutes and at two different heights. To estimate the wind speed at the chosen hub height of 100 m, a logarithmic wind profile has been assumed:

$$U(z) = k \cdot ln\frac{z}{r} \tag{19}$$

Where $U(z)$ is the wind speed at height z, k is a constant, and r is the terrain roughness parameter estimated from the available data. The resulting wind speed occurrency can be well described by a Weibull distribution with a shape parametre β = 1.5937 and a scale parametre η = 10.0247, resulting in a R-squared value of R^2 = 95.24%.

Synthetic time series for wind speed have been generated assuming that the wind always follows such Weibull distribution. Moreover, the time series also respect the constraint that the hourly differences must follow the same discrete probability function of the hourly speed differences in the sample.

The data for solar irradiation has been retrieved from SODA HelioClim-1 Database of Daily Solar Irradiance v4.0 (derived from satellite data) [19] providing hourly values for 11 years, 2005 to 2015. Starting from such data, a typical meteorological year TMY P50 has been assembled, with the methodology from [20] and [21]. More accurate and interesting stochastic and probabilistic modeling can be found in [22] and even more detailed stochastic methods are suggested in [23]. Anyway, because of the lack more accurate weather data, the TMY has been used in the model as it is, since any other method would have been based only on assumptions, and its increase (or decrease) in accuracy relative to reality could not have been quantified.

Electric production in W/m^2 from the array of PV panels has been estimated using the HDKR model in [16]. Accoding to this model, the total useful radiation on the tilted surface is:

$$I_T = I_b + (I_{d,iso} + I_{d,cs} + I_{d,hz}) + I_r \tag{20}$$

Where I_b is the beam or direct irradiance, I_d is the diffuse irradiance, divided into its isotropic, circumsolar and horizon-brightening components, and I_r is the radiation reflected from the ground. The sum of the components in equation (20) can be rewritten as:

$$I_T = (I_b + I_d A_i)R_b + I_d(1 - A_i)\left(\frac{1 + cos\beta}{2}\right)\left[1 + f\ \sin^3\left(\frac{\beta}{2}\right)\right] + I\,\rho_g\left(\frac{1 - cos\beta}{2}\right) \tag{21}$$

Where A_i is an anisotropy index, R_b is the ratio of diffuse radiation on the tilted surface to that on the horizontal plane, β is the tilt angle, $1 + \sin^3\left(\frac{\beta}{2}\right)$ is a correction factor to account for horizon brightening, f is a modulation factor to in $I_{d,hz}$ to account for cloudiness, I is the global horizontal irradiance (GHI) and ρ_g is the ground reflectance.

Geothermal generators are modeled with the simplificative assumption that production is constant at any time, and equal to the nominal installed power. Anyway, frequency regulation is left to thermal groups, since geothermal generators have higher response time and are not suitable for that purpose. According to the analyses of EDA, a geothermal potential seems to exist in Faial up to 7.5 MW.

As for energy storage, in the Faial case study the choice of the storage type has fallen on Li-Ion batteries, in particular on the Tesla PowerPack, The efficiency of charge and discharge in this model is the same and equals to 92.5%; Depth of Discharge (DoD) has been considered 100%, as reported by the manufacturer [24]. Battery lifetime has been assumed as 5 years, after which all storage system must be renewated.

As for the thermal generators, spinning reserve requirements are imposed by the system operator in relation with the wind installed capacity [9]:

$$SR_t = \begin{cases} 50\% \cdot x_1 & if\ HAWS_t > 15\ m/s \\ P_t^{wind} & if\ HAWS_t \leq 15\ m/s \end{cases} \tag{22}$$

The code used for UD+EC problem has been retrieved from [25], and it has been edited for interfacing with the rest of the code. The economic dispatch model takes into account generators' fixed startup cost and operating cost following the relation:

$$Cost_{t,i} = a + b \cdot P_{MWt,i}^{therm} + c \cdot \left(P_{MWt,i}^{therm}\right)^2 \tag{23}$$

Where $P_{MWt,i}^{therm}$ is the power output and a, b, c are coefficients scaled from those reported in [9].

RESULTS

As previously mentioned, the objective function is the difference between the NPV of the new system and the current one, calculated in three sub-scenarios of the current configuration: a basic scenario without any carbon tax, a scenario with a carbon tax of 6 €/ton, which is the current one in Portugal [26], and a third scenario with a hypothetical doubled carbon tax 12 €/ton. Also, since EDA deems geothermal projects below 7.5 MW not feasible as a rule of thumb, although several exceptions exist, for each of the three scenarios two cases have been included, with and without geothermal in the decision variables, for a total of six different scenarios. In each of them, an optimality front has been identified by varying the minimum REF constraint, and keeping constant the minimum EIR constraint of 0.99.

Furthermore, considering the available surface in Faial, the optimal configurations appear to have unreasonable capacities of PV to install, when geothermal is excluded from the decision variables. To fine-tune the results to more realistic solutions, a second round of simulation, whose resulting NPVs are shown in Figure 2, has been performed with a maximum limit of 1.5 MW of PV rated power. Such limitation has been chosen after considering the two EDA projects for PV plants, of 1 MW in Graciosa [27] and 600 kW in Santa Maria [5].

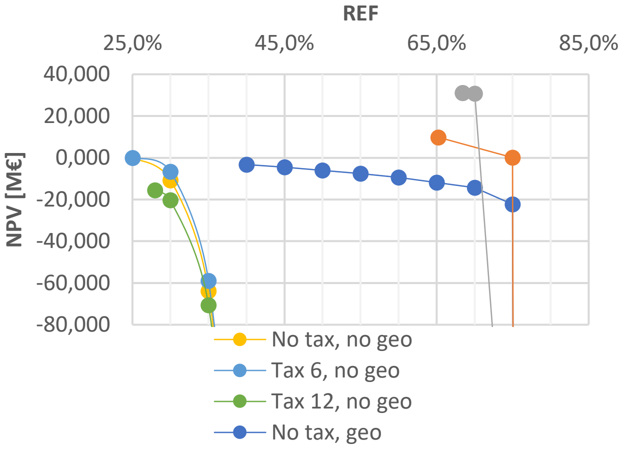

FIGURE 2 – NPV OF THE OPTIMAL DESIGNS WITH PV LIMITATION AT 1.5 MW

Amongst all the resulting optimal configurations, the one which reaches the highest REF at the same time featuring the most realistically feasible configuration is the hybrid wind/geothermal/BESS energy system designed for a REF of 75%. The system requires a total investment of 28.85 M€, of which roughly 78% only for the geothermal plant, and has a NPV of only 43’000€ when compared to the current system configuration in Faial, considering a scenario with the current Portuguese carbon tax of 6 €/ton$_{CO2}$. From the optimisation, a system designed for REF 70% appears to have a definitely higher NPV, roughly 9.8 M€, but the design for 75% has been chosen because is more ambitious in terms of renewable penetration, is more interesting to study due to its higher storage capacity, and still presents a positive NPV.

SENSITIVITY ANALYSIS AND MONTE CARLO SIMULATIONS

In the chosen system design 50% of the energy production comes just from the geothermal plant, while wind is responsible for 17% of the production. Due to the oversizing of the components, the energy that is curtailed every year is a very large amount, summing up to 53% of the total yearly demand. The system relies mostly on only two of the six generators, G4 and G5, while G3 provides a backup when the gap between load and RES production is particularly high. The results have been validated with an optimisation model built in HOMER software, which found a solution very similar to the design determined with the MatLab model.

A sensitivity analysis of the NPV has been performed by varying the electricity retail price, and has resulted, as expected, in a linear trend. The current average electricity price in Faial, is 162.85 €/MWh. One of the measures that can be taken by EDA to increase the secutiry of the project feasibility is to increase slightly the average electricity price, for example to around 180 €/MWh.

To study the impact of uncertainty in the stochastic variables, Monte Carlo simulations have been performed on 2000 different randomly generated time series, both for wind speed and for electric power demand, while the other variables such as the electricity price of 162.85 €/MWh are kept constant. The results of Monte Carlo simulation with HAWS synthetic time series show that, depending on wind speed throughout the year, the NPV can vary even of few million euros, and with the current electricity price has a probability of 52.5% of being lower than zero. With a sufficient increase in retail price, for example to 175 €/MWh, such probability decreases to values close to zero, as visible in Figure 3. As for the electric load variability, the simulation showed that the probability that NPV is lower than zero because of variations in the electric demand profile is 26.2%. Electric load variability has a lower influence on the NPV than wind conditions: fitting the Monte Carlo simulation with a normal distribution, the electric load one presents a standard deviation σ of 0.058 M€, while the HAWS simulation has σ of 0.589 M€, an order of magnitude larger.

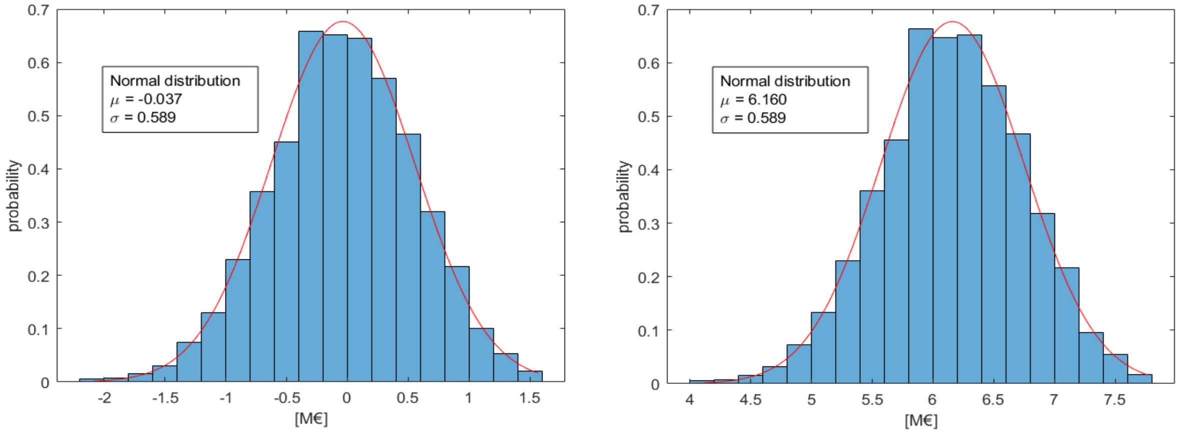

FIGURE 3 – MONTE CARLO SIMULATIONS OF PROJECT NPV DEPENDING ON WIND CONDITIONS, WITH ELECTRICITY RETAIL PRICE OF 162.85 €/MWH AND 175 €/MWH

CONCLUSIONS

The model elaborated in this thesis proved to be a flexible tool with a good level of accuracy in determining the optimal configuration of a hybrid renewable energy system and its financial viability, although overestimating the renewable production. The project in the examined case study appears to be proportioned to EDA's financial possibilities and to be coherent with the framework of investments of the company, totalising an initial investment of 28.85 M€ for a NPV of only 43'000€ when compared to the current system configuration. Moreover, the NPV can rise to roughly 6 M€ with an adjustment of the electricity retail price of around 10 €/MWh. Nevertheless, the presence of subsidies from Portuguese government and European Union is fundamental to support financially new projects of this type and scale.

Wind energy appears to have already reached its saturation capacity in the island of Faial, satisfying around one fifth of the demand. On the other side, photovoltaic technology does not represent a strategic asset due to the low productivity and the land availability constraints that put it in a less preferential position compared to BESS or geothermal. The introduction of BESS alone offers the possibility to increase the renewable energy fraction in a HES, in a proportion increasing with the RES capacity in the system. In the case of Faial for example, the addition of a 6.2 MWh BESS (the size of the BESS in the studied optimal solution) to the current system raises the estimated REF to 27.0% only, against the initial 24.8%. If a geothermal plant of 5.5 MW is present, instead, the presence of the same BESS makes a difference from 71.5% to 75.0%, which means a 60% higher impact from the previous case. The benefits derived from storage can become even higher in presence of RES with a more irregular production such as PV.

Carbon taxes incentivise the deployment of RES by making them more economically convenient, but on the other hand they penalise the company, by increasing costs of fossil generation that can be lowered only up to a certain extent, thus reducing utilities' economic availability for new investments. In the case of Faial, it can be observed that the optimality front in the scenarios with carbon taxes features higher RES and BESS capacities than the one in the scenario without carbon tax, at parity of NPV, thus allowing for higher REF.

Geothermal energy can cover a key role for the energy transition of the Azores, thanks to its constant production throughout the year. In the case of Faial, geothermal is the first technology to enter in the optimal solutions. For example, in the scenario with 6 €/ton carbon tax, a geothermal plant of around 4 MW of capacity can lift the REF in the system to 65%, which can become 75% with a 5.5 MW geothermal plant and 6.2 MWh of BESS, still allowing for a positive NPV.
Anyway, the feasibility of geothermal installations depends mainly on the success of the drilling phase and on the presence of an underground reservoir to facilitate heat exchange.

Considering the increasing deployment of RES, new SR management strategies are needed to make islanded energy systems more flexible and better able to exploit the fluctuating renewable production. Old and rigid SR requirements force curtailment of the renewable energy production, and impose a limit to the possible RES penetration.

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