Development of a modelling and planning tool for renewable microgrids:

The case study of Terceira Island

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Abstract

Due to security reasons in isolated microgrids, when assessing long-term dispatch and capacity investments, it is crucial to consider in sufficient detail the system's short-term variability. The objective of this study is to develop a modelling and planning decision-aid tool for the optimal integration of renewable energy generation in isolated microgrids that combines the short variability with the medium/long-term planning.

The present work proposes the evolution of a short-term economic dispatch model to an integrated operation modelling tool, with several new modelling and planning features. The modelling features developed consist of: the implementation and sizing of different energy storage systems; the development of future demand scenarios with the introduction of electric vehicles, the employment of demand response strategies, or the replacement of inefficient residential equipment (heating, cooling and domestic hot water systems). The main planning feature is the calculation of the levelized cost of electricity (LCOE) for renewable technologies and storage systems that the user would like to test in the energy system, while operation costs, CO_2 emissions and renewable energy shares are also assessed.

The Terceira Island case study was adopted to validate and shape the integrated model, and results demonstrated that this preliminary tool has a great potential for supporting planning decisions, allowing users and grid managers to test several scenarios and obtain valuable parameters to analyze the proposed strategies. The integrated features allow, in fact, to understand whether a new technology, besides being technically feasible, is economically viable with respect to the already existing technologies in the system under study.

Keywords: Economic Dispatch – Microgrids – Renewable Energy – Energy Storage – LCOE

1 Introduction

While transport and industries worldwide still rely on fossil fuels as primary energy vector, the power generation sector has been facing considerable changes, especially in developed countries, where dramatic cost reductions for solar photovoltaic and wind power are driving high levels of investments in renewables and a consequent shift from fossil fuels to renewable resources. However, isolated power systems, like islands and remote areas, still rely mainly on imported fossil fuels for electricity production [1]. Fossil fuel based power generation is able to ensure grid stability and power supply flexibility, which are essential for a safe and correct functioning of the electrical grid, in particular in isolated systems. This dependence from fossil fuels, in most cases exogenous resources, is cause of environmental, energy security and supply issues [2].

Despite the fact that islands face severe energy security, renewable energy resources are frequently abundant, which make them a good opportunity to explore. However, many challenges are hindering the integration of renewable resources on isolated systems. These challenges range from long-term planning to short-term operations and require island system operators to meld all existing technologies and further explore innovative technology options. Political backup is needed as well, in order to promote a variety of issues, such as smart grids, distributed generation, climate policy, system resilience and storage technologies.

Dispatch and capacity investments derived from long-term models may be significantly different if the system's short-term variability is not accounted in sufficient details. From this originates the importance of considering such short-term balancing in long-term energy models in order to derive reliable power system configurations. The research hypothesis of this work, which consists in satisfying the need for a decision-aid modelling tool for isolated hybrid energy systems, is identified within this designated frame. A tool where technical constraints of generation units have a significant impact on both the short-term optimization of production costs and long-term planning. The objective of this work is to improve a previously developed economic dispatch (ED) model [3] and integrate a variety of features in order to create a universal tool that can be implemented for any microgrid under study, either an island or isolated municipality.

The structure of the present work is as follows. In section 2 a literature review on the existing energy system modelling tools and economic dispatch solutions is conducted. Section 3 concentrates on inputs and outputs of the integrated model and the methodologies adopted. In Section 4, the model is validated with the current system configuration of the case study and new features are implemented to give a general overview of the integrated model. Finally, conclusions are reported in Section 0.

2 Literature review

2.1 Energy Modelling Tools

The minimization of operation costs of an energy system mainly relying on fossil fuel consumption, can lead to significant economic benefits [4]. In particular, in small isolated micro-grids, there is a need of a better planning of the long-term investment, and at the same time the need of an economic dispatch tool able to schedule the unit commitment (UC) of the thermal generators in order to minimize fossil fuel consumption and foster the integration of renewable power production, assuring grid reliability. A variety of tools able to partially satisfy the request were found in the literature [5], and the two more widely used are EnergyPLAN [6] and HOMER [7]. Despite the capability of these tools to simulate, with hourly time step resolutions, the dispatch of an energy system, they do not contemplate the input of detailed technical constraints regarding generation units (i.e. startup/shut down times and costs), therefore they are not able to develop a reliable and realistic unit commitment schedule.

The importance of considering such short-term balancing in long-term energy models in order to derive reliable power system configurations is demonstrated in [8]. Cases were found in the literature where the authors felt the necessity of combining a short-term and a medium/long-term tool to simulate the desired scenarios, rather than using an already existing modelling tool. For example, in order to assess the energy reduction potential from the shift to electric vehicles in the Flores Island, Pina et al. [9] used a two-step modelling approach. Firstly, TIMES, a medium-term model, was used to optimize the investment in new generation capacity from RES by taking into account the evolution of electricity demand and fuel prices over a time horizon of 20 years. The outputs of this model, consisting in the quantification of the annual installed capacity, were then used as input for a short-term self-built electricity dispatch model with a one-year time horizon and an hourly temporal resolution.

2.2 Economic Dispatch

In the literature, several studies present a variety of methodologies for economic dispatch of island grids with distributed energy resources. Su and Chuang [10] use genetic algorithms to optimize the integration of a battery energy storage system (BESS) in a given power system. Daily time varying loads, wind power generation and diesel generators operation scheduling are considered together with BESS characteristics such as capacity, installation location and charging/discharging schedules. The problem is formulated as a non-differential combinational optimization problem to solve the ED of the BESS and power units, where the total system cost to be minimized is subject to capacity and system operation constraints. Neves and Silva [11] study the use of domestic hot water (DHW) electric backup from solar thermal systems to optimize the total electricity dispatch of an isolated mini-grid. The proposed approach estimates the hourly DHW load, and proposes and simulates different DR strategies from the supply side, to minimize the dispatch costs of the energy system. This study considers the use of an economic dispatch model that combines the unit commitment problem and the quadratic dispatch method, taking into account the operational restrictions of generation technologies.

3 Integrated Operation Modelling Tool

The architecture of the integrated operation modelling tool, which aims at filling the gaps between short-term and medium/long-term energy planning, can be seen in Figure 1. The modelling tool is defined as "integrated" as it outputs, besides the results of the economic dispatch, valuable parameters for the analysis of investment planning scenarios.

3.1 Model Inputs

3.1.1 Power Supply System

Core inputs to the integrated ED model are the ones regarding the power system configuration, namely: operating constraints of generators, specific fuel costs and renewable resources availability.

While the first two are direct inputs to the model, renewable resources have to be transformed into power production availability. This is achieved through independent functions that convert the available resource at a certain instance, into available electrical power output. While for dispatchable renewable energy (RE) the availability is assumed to be the installed nominal capacity, for non-dispatchable (or variable) RE such as solar photovoltaics (PV) and wind, more complex functions are elaborated.

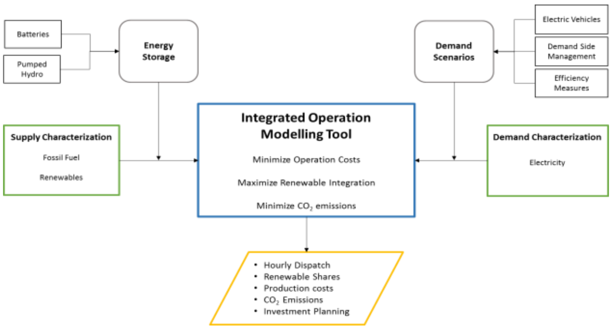

Figure 1: Architecture of the integrated operation modelling tool developed.

For solar PV, an auxiliary function takes as input the daily/monthly mean solar irradiation and the geometry and technical characteristics of the PV arrays, and outputs the hourly production for the time horizon considered. Concerning wind energy, since wind resource is more variable than solar irradiation, and therefore more complex to model, the function takes as input directly a vector of hourly wind speed. Through standard power curves for several sizes of wind turbines the function is then able to calculate an available power output for each hour depending on the wind speed forecasted.

3.1.2 Energy Storage Systems

Different energy storage system (ESS) technologies have different power system applications. Functions simulating Li-ion BESS and pumped hydro energy storage (PHES) systems were integrated into the model. These two technologies were chosen due to their vast perform on multiple applications, which make them the more suitable technologies to be tested on many isolated systems, addressing different storage purposes. While PHES is usually used for larger storage needs, BESS is more commonly used for voltage and frequency regulation due to batteries' high energy and power density [12]. The main inputs that characterize ESS are storage capacity, storage charge/discharge rate and efficiencies. For both ESS technologies, the user is allowed to either input pre-defined parameters, or let the integrated model size the storage system through auxiliary functions. Moreover, another essential input influencing the

ESS behavior is the maximum limit of intermittent variable renewable energy (VRE) generation allowed by the system at every time step in order to preserve grid stability. From now on, this parameter will be referred as VRE penetration factor and indicated with β [13].

Since the main objective of the implementation of an ESS is to increase the total share of RE generation, the assumption that only these would charge the storage system is made. Moreover, priority of charging is granted to non-dispatchable RE such as wind and solar PV. The ESS algorithm is integrated in the initial best path searching phase of the ED model; and the discharge is dictated by a dispatch cost associated to the ESS. Reference values of levelized costs of storage (dispatch costs) for Li-ion BESS and PHES are, respectively, 0.27-0.35 €/kWh and 0.04-0.13 €/kWh[1] [14].

a) Battery Energy Storage System

An iterative technique based on energy balance is adopted for the BESS sizing procedure [15]. The idea is to define an energy curve that represents the excess/deficit of the storable renewable energy with respect to the maximum VRE penetration to the grid. On an average day, batteries are required to cycle between the positive and negative peaks of the energy curve. Therefore, the BESS should at least have a capacity equal to the difference between these two peaks.

b) Pumped Hydro Energy Storage System

The PHES model was developed by a team of the Vulcano Project [16] and was only integrated into the ED model by the author. For this reason, the PHES sizing procedure will not be described in this work. However, inputs necessary are: storage capacity, charge/discharge rate and efficiencies in case these are already known by the user, or RE availability and VRE penetration factor in case PHES sizing is required.

3.1.3 DR, EVs and efficiency measures

The demand response (DR) feature was developed by the author adopting the methodology reported below, while electric vehicles and efficiency measures scenarios were developed by [17] and [18], [19] respectively, and only integrated into the model.

For the DR strategy, the idea is to establish a flexible daily load that can be shifted, subject to daily and hourly constraints which are inputs of the user, in order to exploit VRE surplus. The model uses a linear programming optimization (linprog MATLAB function) to adjust the shape of the demand curve according to renewable resources availability. Concerning the integration of V2G applications to the ED model, several different charging scenarios were accessed from [17]. Depending on EVs' technical characteristics (i.e. battery capacity, energy consumption, maximum charging power) and the percentage of the total fleet converted to EV, the additional load caused by the introduction of EVs is calculated and integrated in the demand profile. Load variations due to the replacement of less efficient residential heating, cooling and DHW technologies is calculated based on the current configuration and the number of houses that would shift from one technology to another.

3.1.4 Energy System Planning

The economic performance between different renewable and ESS technologies and other conventional production technologies can be compared through the Levelized Cost of Electricity (LCOE), which is calculated as the present value of the life cycle cost of the technology over the total energy produced by the system during its useful lifetime. The present value of the total system cost

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[1] Converted from USD with a rate of 1 EUR = 1.13 USD [25].

is known as Net Present Cost, and is calculated as in [20] under the assumption that the study period considered is equal to the useful life of the system:

$$NPC = \sum_{i=0}^{n} C_0 + \frac{C_{RC}}{(1+r)^i} + \frac{C_{RC_n} - RV_n}{(1+r)^n} \qquad (1)$$

Where NPC is the present value of the total system cost, n is the study period in years, r is the discount rate, C_0 is the investment cost, C_{RC} are all O&M costs over the study period and RV is the residual value at the end of the study period. Regarding the total amount of energy produced over the power plant's lifetime, this is calculated for one year and then multiplied for the useful life of the system. While annual variations in energy production are not considered, seasonal variations are accounted for by simulating one week per each season and then extrapolating annual values. LCOE is then calculated according to [20]:

$$LCOE = \frac{NPC}{n \times E_{year}} \qquad (2)$$

Where n is the useful lifetime in years and E_{year} is the annual energy dispatched by the power plant.

3.2 Outputs

Outputs of the ED model are divided into dispatch, economic and environmental that combined support the user in investment planning decisions. Dispatch outputs consist in the optimized unit commitment schedule, with relative generators' power outputs at every time step, and production shares per technology over the study period. Economic outputs are, in fact, the operating costs of each technology. For thermoelectric generators, these correspond to fuel consumption costs. For RE generators and ESSs, associated operating costs are calculated through the (LCOE). LCOE of RE technologies are used to spread the investment and O&M costs of RE power plants over their nominal life time, allowing to economically compare RE and non-RE technologies. Concerning environmental outputs, these consist in the quantification fossil fuel consumption in liters and relative GHG emissions, carbon dioxide in particular.

4 Implementation of the tool

4.1 Model Validation for Terceira Island

The main reason Terceira Island was adopted as a case study is because of the exceptional amount of data made available by the local utility: Electricidade dos Açores (EDA). According to EDA, on December 31st 2014 the electric system of Terceira was composed by three active power plants: a thermoelectric power plant with a total installed capacity of 61.1 MW, a hydropower plant of 1.4 MW and a wind park of 12.6 MW. All power plants belong to EDA, except for 3.6 MW of wind park, which consist in a private windfarm owned by "Companhia Açoriana de Energia Renováveis (CAEN Lda.)". Moreover, power plants exploiting endogenous energy sources such as geothermal and municipal solid waste are currently under construction.

Real production data for a preliminary validation of the model was made available by EDA thanks to a collaboration with the Instituto Superior Técnico (IST) in Lisbon. Real wind and hydro production values were used for the validation of the model.

Simulations were done for several days of all four seasons. The priority list established by the ED model for the solution of the UC problem resulted in accordance with the one provided by EDA. Renewable generators were always committed first, together with one or two large thermal generators, followed by medium-size thermal generators and finally smaller diesel generators. Specific production costs resulted lower in simulations than in real data. This is most likely due to the fact that generators' efficiencies used in the simulations were taken from the products' technical sheets, while in real operation, the age of the generators affects the efficiencies by decreasing them. Concerning CO_2 emissions, average values of days simulated resulted in accordance with the one provided by EDA.

4.2 Implementation of the integrated features

4.2.1 Energy Storage Systems

a) Battery Energy Storage System

The methodology reported in Section 3 was implemented for an autumn day with average wind production, in October. Figure 2 shows the variable renewable energy surplus and deficit for β = 30% of the load.

The optimal BESS characteristics for Terceira according to the methodology adopted and considering that it is a small scale storage system, are shown in Table 1. The storage capacity was calculated from the effective capacity, (Li-ion batteries' SoC has to vary between 20-80% of the total storage capacity [21]), and rounded for practical and commercial reasons. Charge and discharge rates were calculated as C/3, where C is the storage capacity [22]. Efficiencies were obtained from IRENA [14]. As BESS can be considered a future investment, both geothermal and residual solid waste (RSW) power plants were considered fully operational in this scenario.

A sensitivity analysis varying the storage dispatch costs for fixed VRE penetration factors was done in order to assess the hourly behavior of the ESS dispatch. The BESS, for low dispatch costs, resulted capable of completely replacing the medium size thermal generators during restrained peaks and partially replacing these during longer demand peaks.

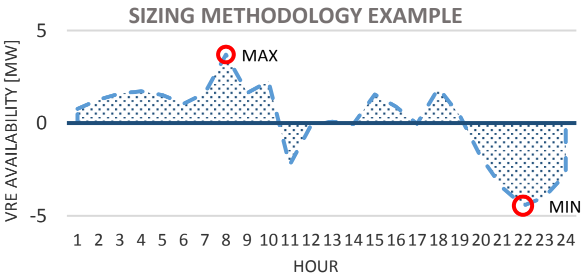

Figure 2: Excess/deficit of RE production on an average day during October in Terceira [23]. VRE production limit set to 30% of load

Table 1: Li-ion BESS optimal sizing considering an average day of October and a curtailment factor of 50%.

Capacity [MWh]	13.5
Charge & Discharge rate [MW]	4.5
Charging efficiency	95%
Discharging efficiency	100%

The impact of integrating a BESS in the system was positive, resulting in a decrease in thermal generators production and, accordingly, a decrease in production costs and CO_2 emissions. The decrease in production costs is due to the fact that, as opposed to thermal generators, BESS has no startup costs.

b) Pumped Hydro Energy Storage

The PHES system, like the BESS, was designed from a vector of curtailed VRE and its parameters are reported in Table 2.

Since PHES has a larger storage capacity, a time horizon of three days was considered for the dispatch simulation. PHES implementation had a positive impact on the energy system, as it increased RE production shares and decreased production costs and CO_2 emissions in the time period considered.

4.2.2 DR, EVs and efficiency measures

Figure 3 shows, as an example, the application of the DR function described in Section 3.1.3 to a week day in autumn with average RE availability.

The VRE penetration factor β in this case is 30%, while the daily shiftable load is 5% of the total load. No hourly constraint was set in this specific case.

Results were positive and indicated that the implementation of the DR strategy increases the penetration of VRE.

Table 2: PHES optimal sizing considering a three-months period Sep-Nov of curtailed VRE [16].

Capacity [MWh]	41.2
Turbines Nominal Power [MW]	4.3
Pumps Nominal Power [MW]	3.6
Round trip efficiency	70%

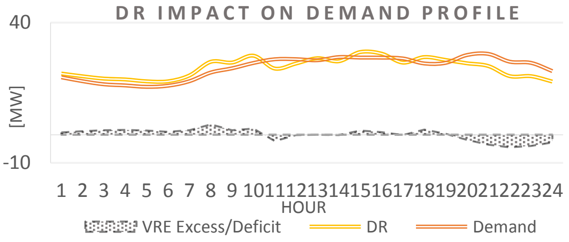

Figure 3: Example of the application of the DR function for day with RE deficit in October, autumn.

Concerning the introduction of EVs, overnight charging scenarios resulted, in general, the best option as they never increased the peak demand. Moreover, since Terceira's demand profile changes significantly depending on the season, different EV charging profiles had different impacts on the demand profile. Results showed that regardless which strategy was adopted, V2G applications caused an increase in total energy consumption and consequently in production costs and CO_2 emissions. However, for this case study, it was possible to establish that depending on the RE availability (different seasons) the integration of EVs allowed the relative VRE penetration shares to slightly increase.

Finally, from simulations of efficiency measures, it emerged that the replacement of heating and cooling systems did not cause substantial variations in demand profiles, and consequently in production shares, because of their little use. Instead, the shift from gas boilers to solar thermal and electric boilers in DHW systems, which is currently being supported by the local utility in Terceira, did have a significant impact on the energy system. In particular, they caused an increase in total energy consumption, and consequent increase in production costs and CO_2 emissions.

4.2.3 Energy System Planning

A scenario considering the implementation of new RE power plants and ESSs in the case study of Terceira was proposed, and the LCOE of each RE technology was obtained from the model. The new energy system configuration proposed presents, in addition to the previously mentioned geothermal and RSW power plants, a double installed wind capacity to simulate a possible future scenario of the energy system. The VRE penetration factor was fixed at 30% of the load for all the simulations, and the characteristics of the BESS and PHES are the ones obtained for the optimal sizing, reported in Table 1 and Table 2 respectively.

Average specific costs for calculating LCOE were found in [14], [23], [24]. For a 10% discount rate, LCOE of the proposed technologies are reported in Table 3.

LCOE for onshore wind is calculated for the new installed capacity only; if the already existing installed capacity was to be calculated, the LCOE would be 0.03 €/kWh. Moreover, as suggested by values found in the literature, PHES presents much lower ranges of levelized cost than BESS.

4.3 General Overview

Finally, a general overview of the integrated ED model is presented in order to have an idea of the variety of features available. The scenario analysed is the same as presented above: RSW and geothermal, double wind capacity and 30% VRE factor. LCOE for RE are the ones reported in Table 3, while for ESS mean values (of the ranges reported always in Table 3) were used: 0.1 €/kWh and 0.2 €/kWh for PHES and BESS respectively. These dispatch costs granted charging and discharging priority to the PHES over the BESS.

Table 3: NPC, energy produced and LCOE for the technologies considered.

	Wind	Geothermal	RSW	PHES	BESS
NPC [k€]	21,100	11,000	7,270	3,194 – 7,600	5,319 – 14,760
En. prod. [MWh]	18,282	25,943	15,485	2,225	4,975
LCOE [€/kWh]	0.058	0.021	0.023	0.06 – 0.14	0.11 – 0.30

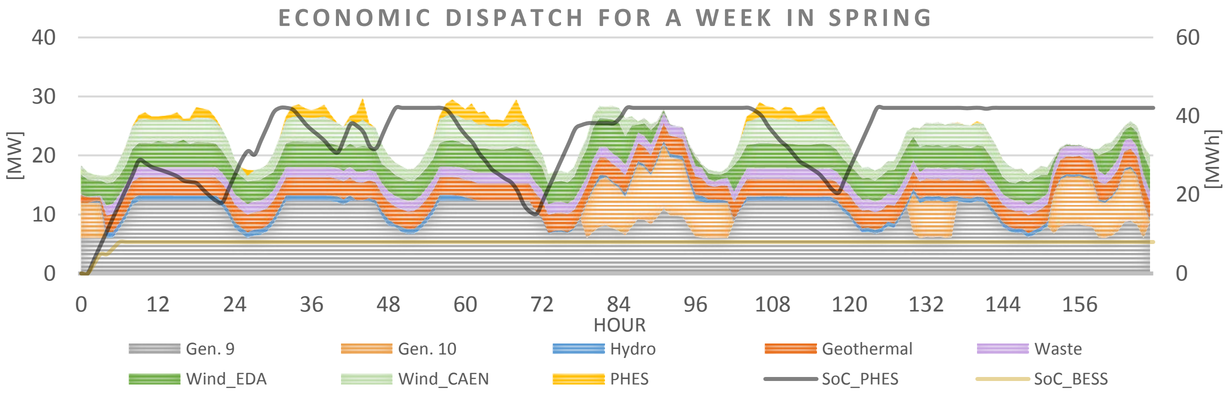

Figure 4: Economic Dispatch for a generic week in spring

Figure 4 shows, as an example, the economic dispatch under the mentioned assumptions, for a generic week in spring. The week is expressed in hourly time-steps, starting from Monday.

Despite being fully charged after only a few hours, the energy stored in the BESS was never dispatched due to its high dispatch costs, while the PHES plays an active role in the ED. Concerning the large thermal generators, one of them was always committed in order to guarantee part of the base load and spinning reserve, while the other was committed when there was a VRE deficit and the PHES discharge rate was not enough to cover this deficit (i.e. Wednesday, Saturday and Sunday). LCOE calculated for geothermal and RSW power plants always resulted lower than the operating cost of the large thermal generator committed at their minimum nominal output. This allowed them to be committed almost constantly at their nominal value, resulting in a capacity (over the week considered) of 98% and 97% for the geothermal and RSW power plant respectively. Non-dispatchable RE production was roughly constant throughout the year, slightly increasing when VRE availability decreased (summer). Wind power production was higher during winter and autumn, decreasing drastically during the summer season. Finally, hydroelectric production was the less significant throughout the year, and contributed only during winter and spring due to climatic reasons. The total amount of energy produced over the year was of 207 GWh and the annual energy production mix, extrapolated from seasonal values, can be seen in Figure 5. Annual production costs, CO_2 emissions and fossil fuels consumption are reported in Table 4. Summer was the season with higher production costs, CO_2 emissions and fuel oil consumption. Only diesel consumption was lower during the summer season, because this fuel is used for the transition phases (i.e. start-up) of thermal generators, and in summer they are turned on/off less frequently. Moreover, diesel oil is used to fuel the smaller generators, which in the scenario analysed were never committed.

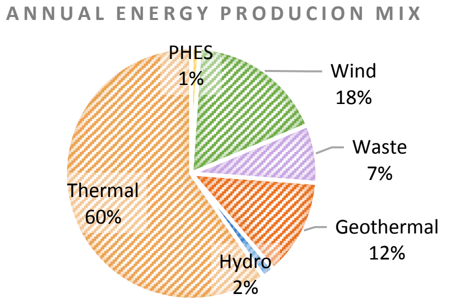

Figure 5: Energy production mix for Terceira Island over a one-year time horizon[1].

Table 4: Production costs, CO_2 emissions and fossil fuel consumption over the year time-horizon.

	Wint. week	Spr. week	Sum. week	Aut. week	Year
Prod. Costs [k€]	294.8	272.8	415.1	326.0	17,012
CO_2 [ton CO_2]	1506	1383	2167	1683	87,598
Diesel [kL]	2.0	1.3	0.6	1.7	72.5
Fuel Oil [kL]	524.2	481.7	756.3	586.1	30,529

5 Conclusions

The integrated economic dispatch model developed in this research work comprehends a variety of features and is capable of providing valuable and substantial techno-economic parameters concerning the energy system under study. In particular, it allows the user to analyze long-term energy planning scenarios that respect an optimal dispatch of the electrical power system taking into account large penetrations of renewable sources.

The model is able to work with a wide range of systems: from those that contemplate extremely high shares of fossil fuel power generation to more hybrid ones, integrating large RE installed capacities.

Regarding the particular case study of Terceira Island, results demonstrated that the implementation of dispatchable RE in Terceira Island has a great potential. In particular, they would be able to partially replace the extremely large shares of fossil fuel based power generation, which are expensive and harmful to the environment. Moreover, the LCOE of both geothermal RSW power plants resulted lower than operating costs of the thermoelectric power plant, which reinforces the advantage of these endogenous RE over fossil fuels. Concerning the expansion of the wind park, this, combined with the implementation of a PHES, would allow a higher penetration of renewable energy production. Instead, BESS, which resulted in more expensive operating costs, was not demonstrated to have a significant role in load levelling. However, frequency regulation aspects were not analyzed in detail in this work, and the possibility of implementing a smaller BESS in order to counterbalance frequency and voltage instabilities of VRE production could be a valuable solution to increase total RE production shares in the system. The tool resulted useful to draw up a list of economically more convenient solutions (all technically feasible), and support decision making in investment planning.

However, future improvements can be made regarding:

- The integration of a forecasting function able to model the stochastic nature of wind resource;
- Associating an additional parameter representing the true cost of the energy stored in the ESS depending on the SoC of the storage system, which would prevent the excessive (and eventually unfeasible) number of charge/discharge cycles when ESS dispatch costs are very low;
- Quantify payback times of investments in these RE technologies.

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