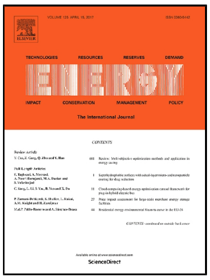

Integration of smart grid mechanisms on microgrids energy modelling

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Highlights

- Modeling and planning framework for isolated renewable microgrids is developed
- Optimal dispatch of renewables considering long-term system feasibility
- The impact of energy storage, demand response, and electric vehicles is studied
- Dispatchable REs have lower LCOE than thermal fueled generation
- PHES decreases VRE curtailment, while BESS presents higher operating costs

Integration of smart grid mechanisms on microgrids energy modelling

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Abstract

Due to security reasons, when assessing long-term planning in isolated microgrids, it is crucial to consider, the system's short-term variability. In this way, the need to develop modelling and planning decision-aid tools for grid managers, towards an optimal integration of renewable energy in isolated microgrids, is emerging. These tools shall combine short-term variability with long-term planning, while addressing multiple smart grid integration challenges.

The present work proposes the evolution of an economic dispatch model to an integrated modelling tool, adding planning features. These consist in the implementation and sizing of different renewable and storage energy systems, and the development of demand scenarios, as the introduction of electric vehicles, demand response strategies, and/or residential efficiency measures. Levelized cost of electricity, operation costs, CO_2 emissions and renewable shares are quantified.

Terceira Island in Azores, is adopted as case study to validate the model. Results show that this tool has a great potential for supporting planning decisions, obtaining valuable parameters to analyze the proposed strategies, as the storage suitability, need of renewable curtailment or cost increase due to electric vehicles deployment. The integrated features allow understanding whether a new technology, besides being technically feasible, is economically viable with respect to the existing system.

Keywords: Economic Dispatch; Microgrids; Renewable Energy; Energy Storage; Levelized cost of electricity

List of Acronyms

BESS – Battery Energy Storage System
DHW – Domestic Hot Water
DR – Demand Response
ED – Economic Dispatch
EV – Electric Vehicles
ESS – Energy storage Systems
LCOE – Levelized Cost of Electricity
NPC – Net Present Cost
O&M – Operation and Maintenance Costs
PHES – Pumped Hydro Energy Storage
PV – Solar Photovoltaic energy
RE – Renewable Energy
RSW – Residual Solid Waste

SoC – State of Charge
UC - Unit Commitment
VRE – Variable Renewable Energy
V2G – Vehicle-to-grid

1. Introduction

Transport and industries worldwide still rely mainly on fossil fuels as primary energy vector. Conversely, the power generation sector has been facing considerable changes. Particularly, this transition is clearer in developed countries, where cost reductions of solar photovoltaic and wind power technologies are driving high levels of investments in renewables energy resources and interconnections [1]. However, isolated power systems, like islands and remote areas, still rely mainly on imported fossil fuels for electricity production [2]. Nevertheless, thermal power generation can 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 a cause of harsh environment, and energy security and supply issues [3].

Even though islands frequently face energy security issues, renewable energy resources are usually abundant which make them a good opportunity to explore. However, many challenges are hindering the integration of renewable resources on isolated systems [4]. These range from long-term planning and investments, to short-term operations, and require system operators to meld all existing technologies and further explore innovative and suitable technology options [5]. Nonetheless, systems feasibility and investments derived from long-term models may be significantly different if the system's short-term variability is not accounted in sufficient detail. As such, the importance of considering short-term balancing in long-term energy models is crucial to derive reliable power system configurations. Moreover, political backup is needed to promote and match a variety of challenging drivers such as smart grids, distributed generation, climate policy or system resilience.

In recent years, several energy system modelling tools have been developed to aid the integration of renewable energy (RE) production in fossil fuel based power systems, and analyze its reliability and cost efficiency [6]. These modelling tools meet different goals and can be classified according to their scope. The main purposes are to simulate the behavior of an energy system and optimize its operation costs, to search for market equilibrium, and to identify and evaluate investment options [6]. To answer to the first two goals, modelling tools are mainly used in grid operation planning, having frequently a short-term horizon, while investment evaluations are more related to long-term analyses of energy system planning. Additionally, the minimization of operation costs of a mostly fossil based energy system can lead to significant economic benefits [7]. That is the case of the majority of small isolated microgrids [8], where better planning of the long-term investment together with an accurate economic dispatch tool is needed. In this way, grid managers would be able to optimize the unit commitment (UC) problem and minimize fossil fuel consumption, while fostering the integration of renewable power production, assuring grid reliability [9].

In this topic, a variety of tools, able to partially satisfy the request, were found in the literature [6], being the more widely used, EnergyPLAN [10] and HOMER [11]. EnergyPLAN is a tool to assist the design of national or regional energy planning strategies by simulating the entire energy system, optimizing it in terms of energy, economic costs or greenhouse gas (GHG) emissions. However, being a tool for macro modeling, it does not respond in detail to the unit commitment problem optimization [10]. On the other hand, HOMER is a microgrids' design tool that simulates and optimizes mostly stand-alone energy systems [12], where the objective of the optimization is to evaluate the economic and technical feasibility for a number of pre-determined technology options, considering variations in technology costs and energy resource availability [6].

Despite the capability of these tools to model with success different energy systems, they lack to optimize with detail the economic dispatch of a hybrid energy system. Per example, failing to consider technical constraints regarding the generation units (i.e. startup/shut down times and costs or spinning reserve), or even maximum variable renewable production, which would reproduce a more realistic operation, since in isolated systems grid resilience is a major issue.

The importance of considering such short-term balancing in long-term energy models to derive reliable power system configurations is demonstrated in [12][13]. 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. For this reason, cases were found in the literature where the authors combined 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 (EV) in the Flores island, Pina et al. [14] used a two-step modelling approach. Firstly, the Integrated MARKAL-EFOM System (TIMES), a medium-term model, was used to optimize the investment in new generation capacity from renewable energy sources (RES) by considering the evolution of electricity demand and fuel prices over a time horizon of 20 years. Then, the outputs of this model, consisting in the quantification of the annual installed capacity, were used as input for a short-term self-built electricity dispatch model with a one-year time horizon with hourly resolution. In the end, the short-term model was used individually for each year to optimize the balance between electricity production from the different energy resources and electricity demand.

Likewise, in the literature several studies presented a variety of methodologies for Economic Dispatch (ED) of island grids with distributed energy resources.

Su and Chuang [15] used genetic algorithms to optimize the integration of a battery energy storage system (BESS) in a given power system, then validating for a real case study. Daily time varying loads, wind power generation and diesel generators operation scheduling were considered together with BESS characteristics such as capacity, installation location and charging/discharging schedules. The problem was formulated as a non-differential combinational optimization problem, where the minimization of total system cost was subject to capacity and system operation constraints.

Neves and Silva [16] studied the use of domestic hot water (DHW) electric backup from solar thermal systems to optimize the total ED of an isolated microgrid. The proposed approach estimated the hourly electric DHW load, proposing and simulating different demand response (DR) strategies from the supply side, to minimize the dispatch costs of the energy system. This study considered the use of an ED model that combined the unit commitment problem and the quadratic dispatch method, considering the operational restrictions of generation technologies.

As seen, each study in literature seems to address a specific goal with a corresponding methodology. Though, there is still the need for a modeling and planning tool that is broaden and customizable to different aims and technologies, but at the same time is specific enough to model in detail the systems' operation.

The scientific contribution 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. The technical contribution of this paper relates to the development of an energy planning tool (Integrated Operation Modelling Tool – IOMT) that considers critical short-term variabilities in long-term investment planning decisions, integrating planning features as demand scenarios, smart-grid mechanisms (as demand response, storage, etc.) or even the deployment of electric vehicles. This tool has its foundations at an economic dispatch model [17], and would help grid managers to monitor and forecast grid stability issues on the short-run, and to compare investments on the long-run, on technical and economic levels, especially in isolated microgrids.

The structure of the present work is as follows. Section 2 concentrates on the inputs and outputs of the integrated model and the methodologies adopted. In Section 3, the Terceira Island case study is presented and validated with the current system configuration of Terceira Island, while in Section 4 the model features are implemented and discussed. An overall overview and discussion is made in Section 5, while final statements are reported in Section 6.

2. Integrated Operation Modelling Tool (IOMT)

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" since, beside modeling the present energy system, fed by the actual electricity demand and supply system configuration, it can also model future energy scenarios, either on the supply or demand side. Furthermore, it can model the implementation of new supply technologies and storage systems, by sizing the optimum capacity and modeling its dispatch. On the demand side, it analyzes the impact of introducing smart grid mechanisms, as the inclusion of demand response strategies, efficiency measures or the introduction of electric vehicles as a way of storing renewable energy surplus. In this way, besides the results of the economic dispatch, the IOMT outputs valuable parameters for the analysis of investment planning scenarios. Further details of the IOMT features are described in the next subsections.

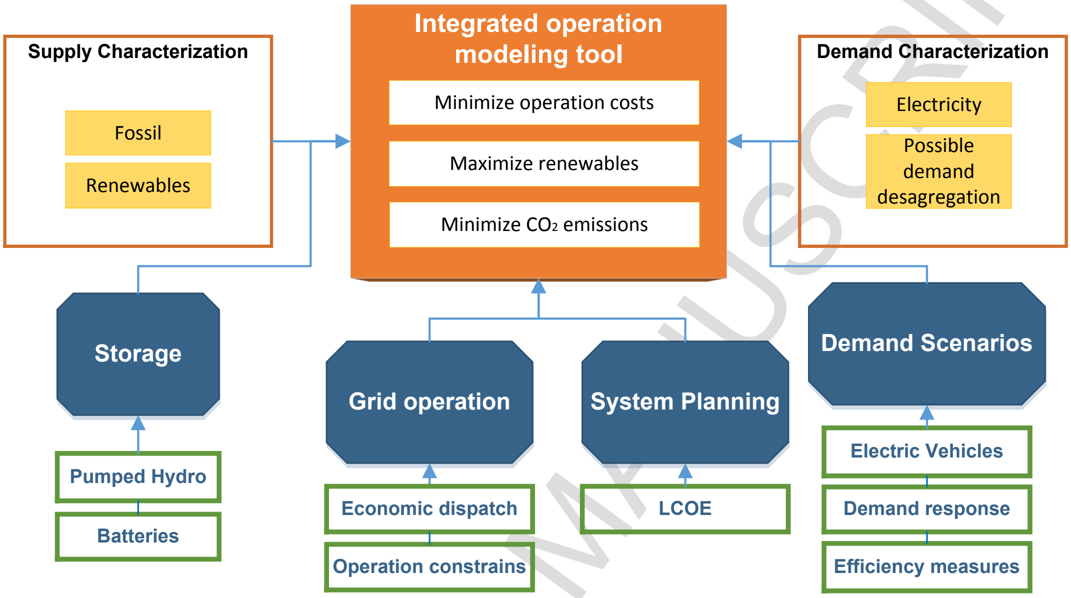

Figure 1 - Architecture of the integrated operation modelling tool

2.1 Model Inputs

2.1.1. Grid operation

The IOMT is based on an economic dispatch model (ED), developed in *MATLAB* [18], whose goal is to minimize the operation costs F_{total} of each generator *i*, for a given demand P_i, at each hour, as given by Equation 1:

$$Minimize\ [\,F_{total}(P_{total})] = \sum_{i=1}^{N} F_i(P_i) \quad (1)$$

Core inputs to the ED model are the ones regarding the system operation namely: number of generators and their operating constrains, 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 electric power output. For dispatchable renewable energy, like biomass, geothermal or residual solid waste (RSW), the resource availability is assumed to be the installed nominal capacity of the power plant. For non-dispatchable renewable energy such as solar photovoltaics (PV) or wind, more complex functions are elaborated to convert forecasted resource power to forecasted power production: in case of solar PV it will depend on the installed area and efficiency of PV panels, and for wind energy it will depend on wind turbines power curves.

2.1.2. Energy Storage Systems

The main goal to introduce storage systems is to match supply with demand needs, particularly when in presence of variable renewable energy. Different energy storage system (ESS) technologies have different power system applications. Two storage systems with different storage horizons were integrated into the model: Li-ion batteries (BESS) and pumped hydro energy storage (PHES). 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 [19].

The main inputs that characterize ESS are storage capacity, storage charge/discharge rates and efficiencies. For both ESS technologies, the user is able to either input these pre-defined parameters, or let the IOMT 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 manager, at every time step to preserve grid stability [20]. From now on, this parameter will be referred as VRE penetration factor and indicated with β.

The main reason to model an ESS in an isolated microgrid is to increase the total share of RE generation, with the assumption that only RE would be used to charge the storage system. 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 were considered, respectively, 0.27-0.35 €/kWh and 0.04-0.13 €/kWh[2] [21].

2.1.2.1. Battery Energy Storage System

An iterative technique based on energy balance is adopted for the BESS sizing procedure [22]. 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 in the grid. On an average day, batteries are required to cycle between the positive and negative peaks of the energy curve. Therefore,

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[2] Converted from USD with a rate of 1 EUR = 1.13 USD [39].

the BESS should at least assure this daily mismatch given by the difference between these two peaks.

2.1.2.2. Pumped Hydro Energy Storage System

The PHES model was developed by a team of the *Vulcano Project* [23] having been integrated into the IOMT model by the authors. PHES sizing procedure was done in such way to assure the storage of VRE excess during weekends, since demand levels are lower than in weekdays, and in isolated systems, this leads to the VRE curtailment. For the operation, the PHES inputs are storage capacity, charge/discharge rate and round-trip efficiency, in case these are already known by the user, and VRE availability and penetration factor, in case PHES sizing is required.

2.1.3. Demand Scenarios

2.1.3.1. Demand Response

The demand response is a way to take advantage of partial load flexibility to best manage the match between energy supply and demand. According to [24] *DR is voluntary adjustment, and can be made by the end-user as a response to a price signal, or taken by a counter-party, based on an agreement with the end-user*. Since this tool addresses mainly grid operation and reliability, DR is here modeled on a centralized logic, by the grid manager. The idea is to establish a percentage of flexible daily load that can be shifted, subject to daily and hourly constraints, which the user inputs, to absorb 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.

2.1.3.2. Electric Vehicles

In the literature it has been observed an increasing interest on electric vehicles integration on the energy system planning [14], [25]. For this reason, they were selected as a feature to be integrated on the IOMT. However, in this application, EVs were only considered to charge from the grid, and not as energy suppliers.

Concerning the integration of Vehicle-to-Grid (V2G) applications to the IOMT model, four different hourly charging scenarios were accessed from [26], and presented in Figure 2. Depending on EV 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.

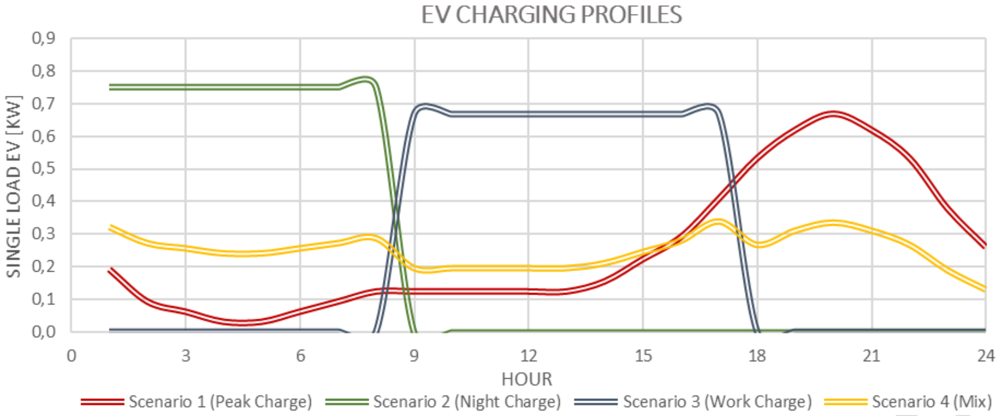

Figure 2 - EV charging scenarios [22]

2.1.3.3. *Efficiency Measures*

The efficiency measures mentioned, consider a technology shift from older equipment based on fossil fuel vectors to electric ones, in order to take full profit of endogenous and renewable resources. In this way, the residential sector, that in small and isolated communities is the largest electricity consumer, was selected for such efficiency measures.

As such, the replacement of less efficient residential heating, cooling and DHW technologies by more efficient ones was considered. Thus, load variations in total islands' demand have been computed, based on the current configuration and the number of houses that would shift from one technology to another (customizable) [27], [28], and respectively, integrated into the model.

2.1.4. 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). The LCOE 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 is known as Net Present Cost (NPC), and is calculated as in [29] under the assumption that the period considered is equal to the useful life of the system, shown by Equation 2:

$$NPC = \sum_{i=0}^{n} C_0 + \frac{C_{RC}}{(1+r)^i} + \frac{C_{RC_n} - RV_n}{(1+r)^n} \tag{2}$$

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 operation and maintenance (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 lifetime, it is calculated for one year and then multiplied for the useful lifetime of the system. While annual variations in energy production are not considered, seasonal variations are taken into account by simulating one week per each season and then extrapolating annual values. LCOE is then calculated by Equation (3), according to [29]:

$$LCOE = \frac{NPC}{n \times E_{year}} \tag{3}$$

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

2.2 Outputs

Outputs of the IOMT model are divided into dispatch, economic and environmental results, which once 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 (hourly), and production shares per technology over the study period;
- Economic outputs are, in fact, the operating costs of each technology. While for thermoelectric generators, these correspond to the fuel consumption costs (including start-up and shut down costs), for RE generators and ESSs, the associated operating costs are calculated through the LCOE. LCOE of RE technologies is used to spread the investment and O&M costs of RE power plants over their lifetime, allowing to economically compare RE and non-RE technologies;
- The environmental outputs consist in the quantification of fossil fuel consumption in liters and relative GHG emissions, carbon dioxide in particular.

3. Validation of IOMT for Terceira Island

Terceira Island is located in Azores Archipelago, Portugal, in the middle of the Atlantic Ocean, with a population of around 56,000 residents [30]. The island has an installed capacity of 71.6 MW, having registered in 2015 an electricity consumption of 179 GWh, with a maximum peak load of 34 MW during the winter season [31].

The main reason Terceira Island was adopted as a case study is due to the exceptional amount of data made available by the local utility *Electricidade dos Açores* (EDA), when collaborating for the *Vulcano* Project [23] with the *Instituto Superior Técnico* (IST) in Lisbon.

According to EDA, on December 31st 2014 the electric system of Terceira was composed by four active power plants:

- a thermoelectric power plant with a total installed capacity of 61.2 MW,
- a hydropower plant of 1.4 MW,
- a wind park of 9 MW,
- a private wind park of 3.6 MW.

All power plants belong to EDA, except for the 3.6 MW of wind park, which consists of a private windfarm (owned by *CAEN, Lda*). Moreover, power plants exploring endogenous energy resources such as geothermal and municipal residual solid waste are currently under construction, and will provide, when fully installed, additional 3 MW and 1.8 MW respectively [32][33].

In order to validate the IOMT model for the case study of Terceira Island, simulations were done for several days (weekdays and Saturdays and Sundays) of all four seasons, with the current configuration of the supply system of the island, excluding all integrated features. Real production data, including wind and hydro production values, were used for a preliminary validation of the model.

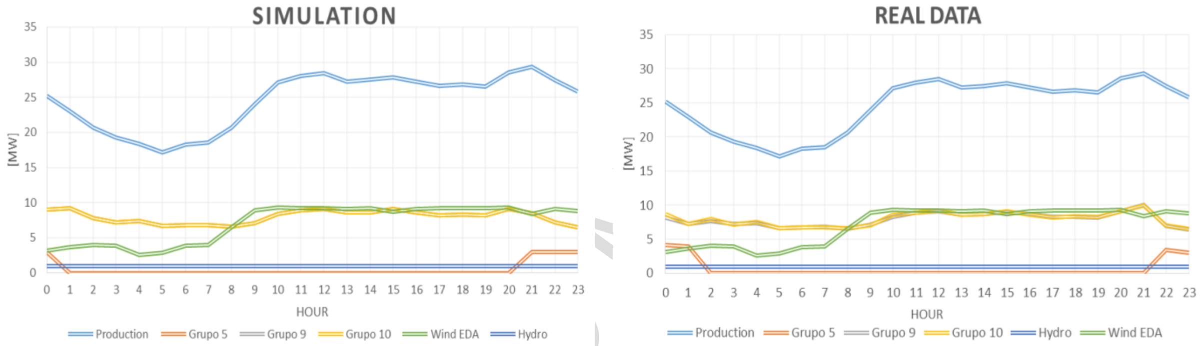

Figure 3 - Comparison between economic dispatch of simulated and real data, for a spring weekday

As observed in Figure 3, the priority list established by the economic dispatch for the solution of the unit commitment problem resulted in accordance with the one provided by EDA. Renewable generators (*Hydro and Wind EDA*) were always committed first, together with one or two large thermal generators (*Grupo 9 and Grupo 10*), followed by medium-size (*Grupo 5*) thermal generators and finally smaller diesel generators.

However, specific production costs resulted lower in simulations than in real data. This is mostly due to the generators' efficiencies used in the simulations were taken from the products' technical sheets, while in real operation, the older age of the generators decrease their efficiency. This fact is directly related to the specific CO_2 emissions validation in Figure 4, where the average value of eight simulated days resulted in accordance with the yearly average of specific emissions provided by EDA.

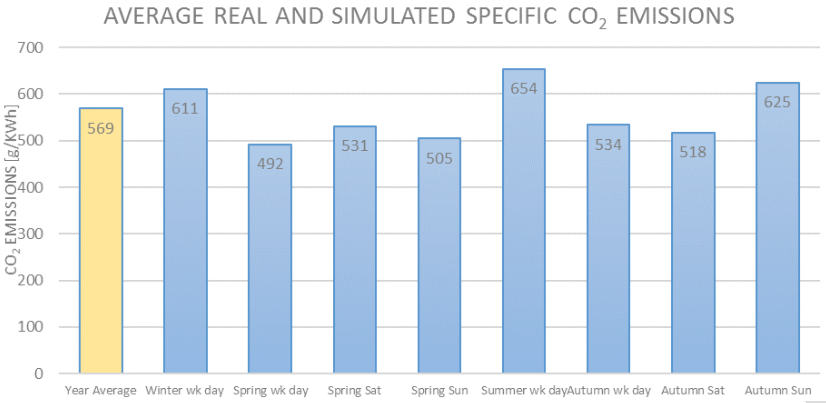

Figure 4 - Comparison between CO2 emissions in simulated days and year average provided by EDA [34].

4. Implementation and analysis of the integrated features of IOMT

In this section, the integrated features previously described in Section 2 are implemented for Terceira Island case study. The scenario considered takes into account both geothermal and residual solid waste power plants as fully operational, since the two plants will in fact be ready and running by 2017.

4.1 Energy Storage Systems

4.1.1 Battery Energy Storage System

The methodology reported in Section 2 was implemented for an autumn day in October, with average wind production, since as previously mentioned, BESS was considered to have a daily storage horizon. Figure 5 shows the variable renewable energy surplus and deficit, for which the BESS was sized, for a VRE penetration factor, β of 30% of the load.

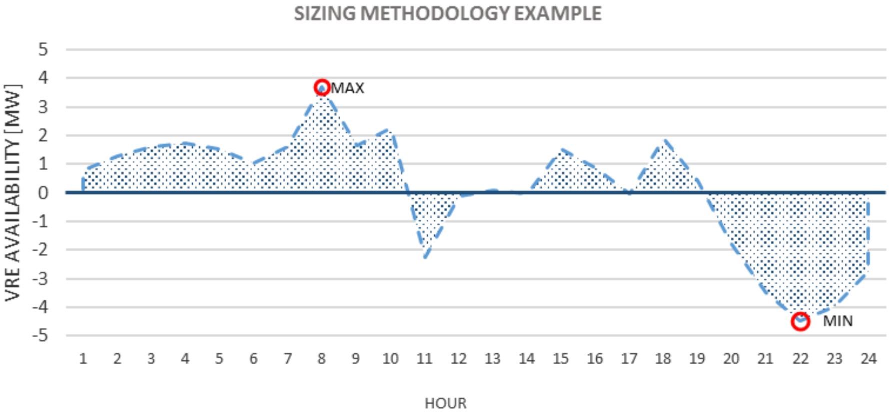

Figure 5 - Excess/deficit of RE production on an average day during October in Terceira [23]. VRE production limit set to 30% of load

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' state of charge (SoC) has to vary between 20-80% of the total storage capacity [35]), and rounded for practical and commercial reasons. Charge and discharge rates were calculated as C/3, where C is the storage capacity [36]. Efficiencies used were obtained from IRENA [21].

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%

A sensitivity analysis varying the storage dispatch costs for fixed VRE penetration factors was done, to assess the hourly behavior of the ESS dispatch. The BESS, for low dispatch costs, was capable of completely replacing the medium size thermal generators, during isolated peaks and partially replacing these during longer demand peaks. Figure 6 reports a day in January, of the system operating with BESS. It is observed that the BESS was charged overnight, with *Wind_CAEN* surplus, and dispatched during the evening peak, when large conventional generators, geothermal, RSW, hydro and wind capacities were already on their full potential. 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 explained by BESS having no startup costs, as opposed to thermal generators.

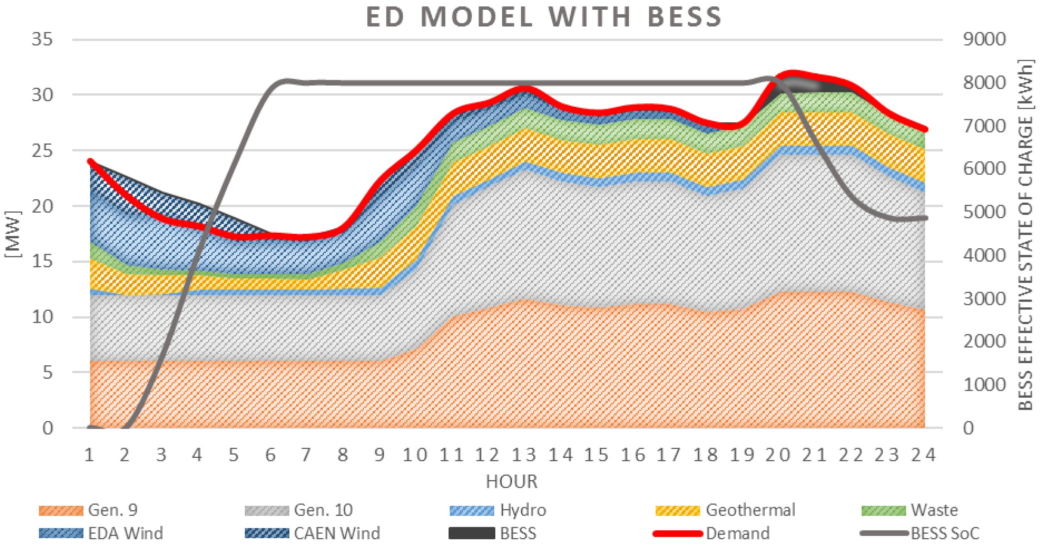

Figure 6 - Economic Dispatch with a 13.5 MWh BESS at 0.12 €/kWh for an average week day of January, winter.

4.1.2 Pumped Hydro Energy Storage

The PHES system was also designed from a vector of curtailed VRE, being the storage parameters reported in Table 2.

Table 2: PHES optimal sizing considering a three-months period Sep-Nov of curtailed VRE [23].

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

Since PHES has a larger storage capacity, a time horizon of three-day storage 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 period considered. An example with a VRE penetration factor of 40% during a three-day period (Sunday – Tuesday) in October can be seen in Table 3.

Table 3: Impact of the PHES on the energy production shares, production costs and CO_2 emissions for a three-day time-period in October.

	β=40%	
	No Storage	PHES
Wind	29.6%	31.3%
Thermal	70.4%	68.7%
Prod. Costs [€]	171,950	170,620
CO_2 emissions [tonCO_2]	897.7	884.5

4.2 Demand scenarios implementation

4.2.1 Demand response

Figure 7 shows, as an example, the application of the DR function described in Section 2.1.3 to a weekday in autumn with average RE availability, considering a VRE penetration factor β of 30%, while the daily shiftable load is 5% of the total daily load. No hourly constraint was set in this specific case.

Results were able to introduce operating cost savings and increase the RE share in the system. For this configuration, RE shares increase by 2.7%, while daily production costs and CO_2 emissions decrease by 3.4% and 3.3% respectively.

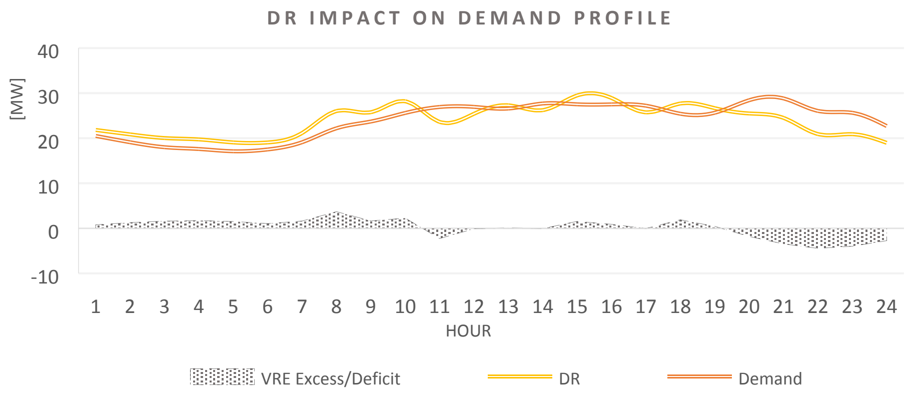

Figure 7 - Example of the application of the DR function for day with RE deficit in October, Autumn.

4.2.2 Electric vehicles deployment

Concerning the introduction of EVs, with a 25% share of total light vehicle fleet, overnight-charging scenario resulted, in general, as the best option, since they never increased the peak demand (Figure 8). Moreover, since Terceira's demand profile changes significantly depending on the season, different EV charging profiles had different impacts on the demand profile.

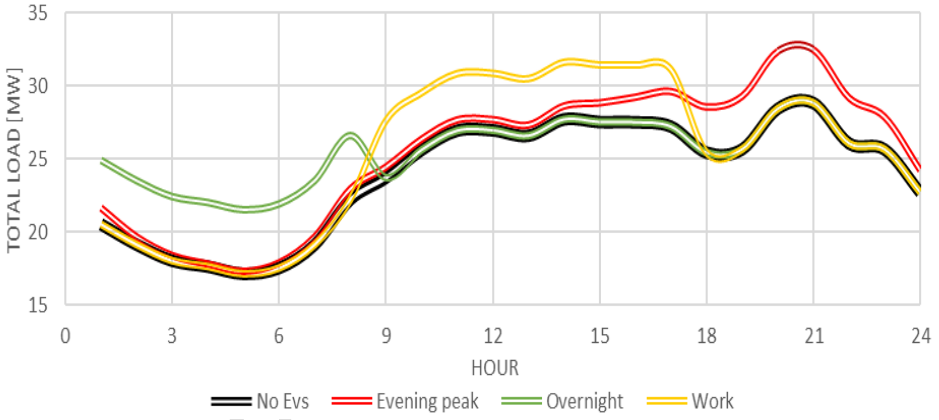

Figure 8 - Impact of EV charging scenarios in Terceira's total load, for an Autumn day

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) and charging strategy adopted, the integration of EVs allowed the relative RE penetration shares to slightly increase. This is observable in Table 4, where the reference case is without EVs, and "Evening", "Overnight" and "Work" are three different charging profile scenarios. The maximum wind penetration is intended as hourly over the day considered.

Table 4: Impact of EV charging profiles on RE shares, production costs and CO_2 emissions for weekdays in autumn and summer.

	Autumn	**Summer**

	Reference	Evening	Overnight	Work	Reference	Evening	Overnight	Work
Wind	26.0%	25.2%	27.5%	25.0%	5.2%	4.9%	4.9%	4.9%
Geothermal	10.8%	10.4%	11.5%	10.2%	11.5%	10.9%	10.9%	10.9%
RSW	5.8%	5.7%	6.8%	5.5%	6.9%	6.5%	6.5%	6.5%
Thermal	57.4%	58.8%	54.2%	59.3%	76.4%	77.6%	77.6%	77.6%
Max Wind Penetration	35.6%	36.2%	36.8%	33.9%	13.0%	12.4%	13.0%	11.6%
Prod. Costs [€]	48,920	51,669	49,030	52,168	63,990	68,384	67,409	68,182
CO_2 emissions [$tonCO_2$]	255.4	269.8	256.0	272.2	334.0	357.0	351.9	355.9

4.2.3 Efficiency measures

Finally, from the simulations of efficiency measures, it emerged that the replacement of heating and cooling systems (radiators and fans to heat pumps) did not cause substantial variations in demand profiles, and consequently in production shares, due to the mild climate, the low usage of these type of systems and their high efficiency. However, the shift from gas boilers to solar thermal and electric boilers in DHW systems (in a share of 50% each for the totality of residential houses), which is currently being supported by the local utility in Terceira, did have a significant impact on the energy system, as seen in Figure 9. In particular, it increased the total electricity consumption, production costs and CO_2 emissions in 12%, while peak demand increased 19%[3].

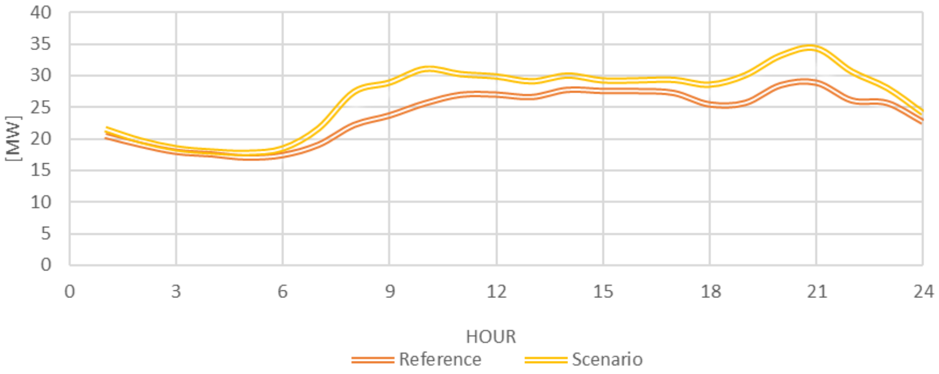

Figure 9 - Impact of the 50% solar thermal collectors and 50% electric water heaters scenario on the daily demand of an average weekday in Autumn.

4.3 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

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[3] These calculations did not take into account the savings in gas consumption since the aim of the study was to analyze the impact on the electric grid.

mentioned geothermal and RSW power plants, a doubled 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 were the ones computed for optimal sizing, reported in Table 1 and Table 2, respectively. Average specific costs for calculating LCOE were found in [21], [37], [38]. LCOE for onshore wind is calculated for the new installed capacity only (the LCOE calculated with the actual capacity would be 0.03 €/kWh). For a 10% discount rate, the computed LCOE is reported in Table 5.

Table 5: 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
Energy production [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

As seen in Table 5, the LCOE of endogenous resources such as wind, geothermal and RSW result lower than operational costs of thermal power plants running on imported fossil fuels (~0.12 €/kWh). Moreover, as suggested by values found in the literature, LCOE associated to pumped hydro storage is in the same range of other power production technologies present on the island, while for BESS the range results significantly higher. Nonetheless, in islands, endogenous resources are valorized according to many criteria, not only by economic ones, since they struggle with external dependency. For this reason, priority shall be granted to variable renewable resources, despite small fluctuations in operating costs. Nonetheless, for other case studies were RE costs are more profoundly connected to the energy market, using specific costs for the LCOE calculation may influence LCOE performance, namely when they are subject to feed-in tariffs.

5 Discussion of the IOMT

Finally, a general overview of the IOMT modeling several days is presented in order to have an idea of the variety of features available and how they coexist in the energy system.

The scenario analyzed is the same as presented before: operational RSW and geothermal, doubled wind capacity and 30% VRE factor. The LCOE considered for RE is the one previously reported in Table 3, while for ESS, mean values (of the ranges reported 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.

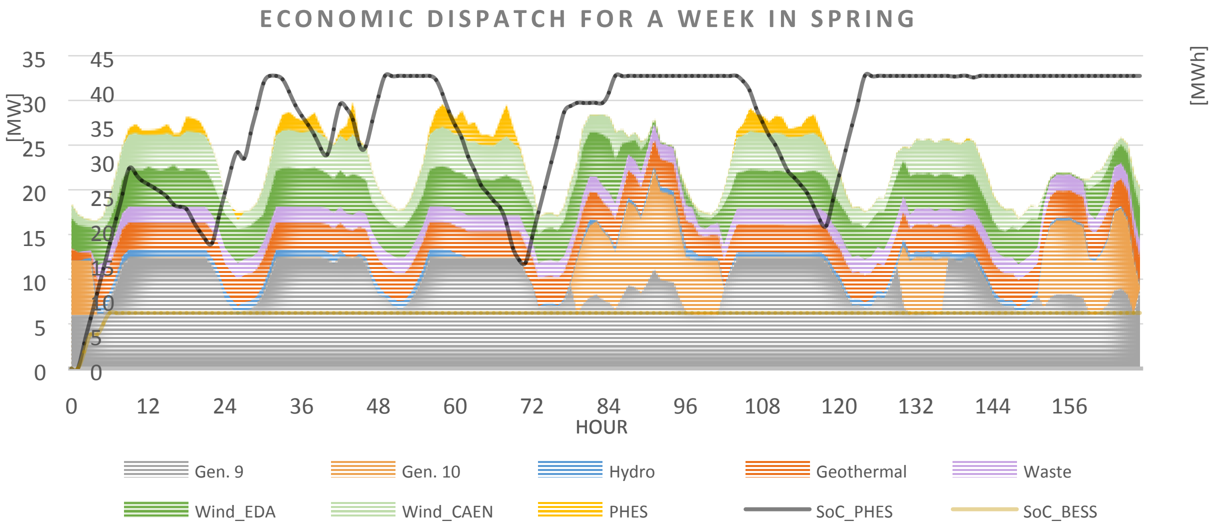

Figure 10 - Economic Dispatch for a generic week in Spring

Figure 10 shows, as an example, the economic dispatch under the mentioned assumptions, for a typical 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. Whereas, the PHES played an active role in the ED. Concerning the large thermal generators, *Gen_9* was always committed in order to guarantee part of the base load and spinning reserve, while *Gen_10* 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 resulted always 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.

Reporting on annual results, non-dispatchable RE production (geothermal and RSW) 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 11

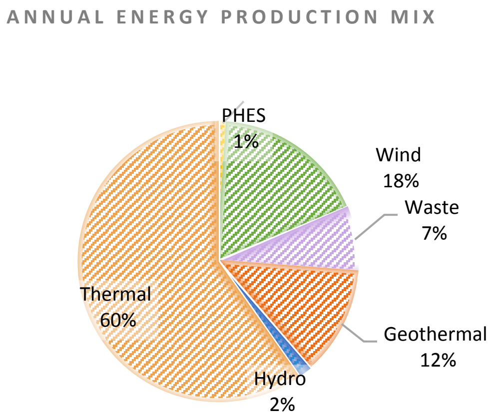

Figure 11 - Energy production mix for Terceira Island over a one-year time horizon

Annual and seasonal production costs, CO_2 emissions and fossil fuel consumption are reported in Table 6. Summer was the season with the highest production costs, CO_2 emissions and fuel oil consumption, mainly due to tourism related load increase. Only diesel consumption was lower during the summer season, as this fuel is used only 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 analyzed were never committed.

Table 6: Production costs, CO_2 emissions and fossil fuel consumption over the year time-horizon.

Season	**Winter week**	**Spring week**	**Summer week**	**Autumn 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

6 Conclusions and future work

The Integrated Operation Modelling Tool developed in this research work comprehends a variety of features that can provide valuable and substantial techno-economic indicators. It allows the user to analyze long-term energy planning scenarios that respect an optimal dispatch of the electrical power system considering large penetrations of renewable sources.

The model can 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 case study, results demonstrated that the implementation of dispatchable RE in Terceira Island has a great potential. They would be able to partially replace the extremely large shares of fossil fueled power generation, which is expensive and harmful to the environment. Moreover, the LCOE of both geothermal and RSW power plants was found to be lower than the operating costs of the thermal power plant, which reinforces the advantage of these endogenous RE over fossil fuels. Concerning the expansion of the wind park, combined with the implementation of a PHES system, it would allow a higher penetration of RE production, and thus a relaxation of the VRE penetration factor. Additionally, BESS, which resulted in more expensive operating costs, has 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 to counterbalance frequency and voltage instabilities of VRE production could be a valuable solution.

The tool resulted useful for grid managers to draw up a list of economically more convenient solutions (all technically feasible), and support decision making in investment planning. Either on the supply side - testing the coexistence of different types of energy storage and renewable technologies, and their relative importance to the system balance; either on the operation side - pointing to the relaxation of operation constraints with energy storage and dispatchable RE, allowing an increase in the penetration factor of VRE; or even on the demand side - giving an exploratory overlook of how public policy on energy efficiency, transports, and smart grid mechanisms, as demand response, can influence the island energy system.

However, future improvements to the tool can be made regarding the integration of possible load fluctuations and its effects on the efficiency of the different supply technologies, as also a forecasting function able to model the stochastic nature of wind resource. Furthermore, the model would also benefit of associating an additional parameter representing the true cost of the energy stored in the ESS depending on the SoC of the storage system. This would prevent the excessive (and eventually unfeasible) number of charge/discharge cycles when ESS dispatch costs are very low.

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