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Sustainable Energy Systems Planning Tool for Islands

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Abstract

One way to respond to the multiple challenges that climate change poses is to reduce CO2 emissions, in particular on the energy sector. Thus, this energy transition for a more sustainable energy system has reduce energy generation from fossil fuels and increase energy production from renewable energy sources. Isolated energy systems as microgrids with local renewable generation represent both an opportunity for decarbonization and a technological challenge. With increasing renewable penetration and new technologies as energy storage systems and demand response techniques, the modelling and simulation of these energy systems and their operation become of paramount importance.

Reliable and accurate modelling tools are then needed as a support to energy grid managers and to investment planning decision-makers. Several software and tools with different characteristics already exist, but as the energy systems are rapidly changing, these tools have also to adapt.

The work here presented aims at analysing and further developing an already existing modelling tool, which was created to simulate the energy systems of the Azores islands. This tool, called Vulcano, is developed in MATLAB and follows an economic dispatch model with linear optimization. However, several improvements were needed to make it more reliable and versatile for any energy system.

To validate the tool, the energy system of Terceira Island was simulated, and the results were compared to the ones of the commercial software HOMER Pro. To improve the ability of the tool to simulate high renewable penetration systems new features were added and modifications were made to the code such as the implementation of a different way to calculate the priority for the commitment of generators or the development of a function that would calculate the wind power output.

An analysis focused on the storage systems integration in the tool and its operations was carried out and consequently several solutions were tested and implemented. Ultimately, the Madeira Island energy system was simulated to test the changes made.

The results showed substantial improvements: the dispatch of generators was very close to the one obtained from the commercial tool, and the storage operations were closer to reality.

Riassunto

Uno dei modi per rispondere alle molte sfide che il cambiamento climatico ci pone davanti è quello di ridurre le emissioni di CO_2, in particolare nel settore energetico. La transizione energetica verso un sistema più sostenibile deve ridurre la produzione di energia da fonti fossili e aumentare quella da fonti rinnovabili. Sistemi energetici isolati che funzionano come microgrid con produzione locale da energie rinnovabili, rappresentano sia un'opportunità per la decarbonizzazione, sia una sfida tecnologica. Con penetrazioni di energia rinnovabile in crescita e con nuove tecnologie come l'accumulo o tecniche di demand response, la modellazione e simulazione di questi sistemi e del loro funzionamento diventa di fondamentale importanza.

C'è bisogno di strumenti di modellazione accurate e affidabili per supportare i gestori delle reti energetiche e coloro che decidono sulla pianificazione degli investimenti. Molti software e strumenti con diverse caratteristiche esistono già, ma con il rapito cambiamento dei sistemi energetici, anche questi devono adattarsi.

Il lavoro presentato in questo documento vuole analizzare e continuare a sviluppare uno strumento di modellazione già esistente, che era stato creato per simulare il sistema energetico di alcune delle isole Azzorre, in Portogallo. Questo strumento, chiamato Vulcano, è stato sviluppato in MATLAB e usa un modello di dispacciamento economico con ottimizzazione lineare. Al fine di renderlo più affidabile e versatile per diversi tipi di sistema energetico, c'è stato bisogno di apportare molti miglioramenti.

Per validare questo software, è stato simulato il sistema energetico dell'isola Terceira e i risultati ottenuti sono stati confrontati con quelli del software commerciale HOMER Pro. Per migliorare l'abilità del tool a simulare sistemi ad alta penetrazione di rinnovabili, alcune funzionalità sono state aggiunte e alcune modifiche sono state fatte al codice, come ad esempio l'implementazione di un diverso modo di calcolare la priorità delle varie unità di generazione e lo sviluppo di una funzione che calcolasse la potenza eolica prodotta.

È stata svolta, inoltre, un'analisi focalizzata sull'integrazione dei sistemi di accumulo e sul loro funzionamento e successivamente alcune soluzioni sono state sviluppate e teste. Infine, il Sistema energetico dell'isola di Madeira è stato simulato per testare in cambiamenti apportati.

I risultati mostrano miglioramenti sostanziali: da un lato il dispacciamento delle unità di generazione risulta molto simile a quello ottenuto con il software HOMER, dall'altro il funzionamento dei sistemi di accumulo si è avvicinato a quello reale.

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Acronyms

BESS – Battery Energy Storage System

CAES – Compressed Air Energy Storage

DR – Demand Response

EDA - Electricidade dos Açores

EEM – Empresa de Electricidade da Madeira

ESS – Energy Storage Systems

GHI – Global Horizontal Irradiation

GUI – Graphical User Interface

HRES – Hybrid Renewable Energy Systems

NG – Number of Generators

NPC – Net Present Cost

NT – Number of Time steps

O&M – Operation & Maintenance

PHES – Pumped Hydro Energy System

RES – Renewable Energy Sources

RSW or RSU –Residual Solid Urban Waste

VRE – Variable Renewable Energy

SDG – Sustainable Development Goals

SoC – State of Charge

UC – Unit Commitment

1 Introduction

1.1. Motivation

Global energy-related CO_2 emissions grew 1.7% in 2018 to reach a historic high of 33.1 Gt CO_2 as presented in the World Energy Outlook of 2019 [1, pp. 46-47]. Even though the energy-related emissions have not increased further in 2019 [2], it is of paramount importance that in future the cumulative CO_2 emissions decrease to limit global warming to 1.5°C [3]. The global energy demand is expected to keep growing in the *Current Policies* and *Stated Policies* IEA scenarios[1], and the trend will increase even more due to increased demand for cooling and desalination in the Middle East and because of the rising economy and population growth in Africa [1]. Electricity use is growing at more than double the pace of overall energy demand in the *Stated Policies* scenario, raising its share in the total energy consumption from 19% in 2018 to 24% or 31% in 2040 regarding the *Stated Policies* and the *Sustainable Development* scenario, respectively[2]. Therefore, to meet the future electricity demand and at the same time reducing CO_2 emissions it is necessary to drastically reduce the energy production from fossil fuels (especially from coal and oil) and to increase the share from renewable energy sources (RES).

On the other hand, the growth of renewable energies is resulting in the cost reduction of renewables' technologies and consequently on the energy produced by renewables. In fact, as highlighted by [4]: *"For projects to be commissioned in 2020, 77% of the onshore wind project capacity and 83% of the utility-scale solar PV in the IRENA auction and PPA database have costs that are lower than the cheapest fossil fuel-fired power generation option for new generation."*. This trend, along with the increasing cost of coal, oil and natural gas fuels [5], is favouring new investments in renewable energies making it grow rapidly: the global renewable share in the

[1] The Current Policies Scenario shows what happens if the world continues along its present path, without any additional changes in policy: the energy demand would increase of 1.3% every year. The Stated Policies Scenario incorporates today's policy intentions and targets: the energy demand would increase of 1% every year. [1]
[2] The Sustainable Development Scenario maps out a way to meet sustainable energy goals in full, requiring rapid and widespread changes across all parts of the energy system; this scenario is aligned with the Paris Agreement.

total final consumption could increase from the 10% in 2018 to 18% or 32%, respectively, in the *Stated Policies* Scenario and *Sustainable Development* Scenario in 2040 [1].

With these changes, the energy system and the electrical grid will have to change drastically, adapting to the higher renewable shares. Nonetheless, due to their highly intermittent nature, renewable energies are unpredictable, which represents a further obstacle to maintain grid stability, hence a challenge for the grid deployment, investment and managers.

In this context, off-grid hybrid renewable energy systems (HRES) represent an even bigger challenge due to higher renewable penetrations, which might stress the reliability and stability of the grid. Nevertheless, stand-alone HRES and mini-grids are the currently best solution for rural areas, where energy access is a real struggle [6], and that is why energy access for all is one of the targets of the 2030 United Nations Sustainable Development Goals (SDG), SDG 7 - Affordable and Clean Energy [7]. Off-grid energy systems also represent an opportunity to decarbonise island energy systems which have always been strongly dependent on fossil fuels, even though many have started to integrate renewables into their electricity supply mix or plan to do so [8]. This transition strongly depends on "*the ability of the local power system to integrate renewable energy technologies while maintaining adequate levels of security and reliability*" [9]. The technical challenges for the grid intensify especially if the penetration of variable renewable energies such as solar PV and wind power increases.

The creation of microgrids can foster the integration of renewables in isolated energy systems and increase reliability. A microgrid is defined by [10] as "*a small-scale localized energy system consisting of various distributed generators, energy storage devices, and local loads*", which makes them particularly suitable for isolated islands. Microgrids are, in fact, the effective technology to integrate high-penetration renewable energy while ensuring the stable and reliable electricity supply, avoiding power losses from long-distance transmission. Microgrids can also be integrated with solutions such as smart grid technologies, like energy storage, demand response (DR), or distributed generation, in order to increase the overall efficiency and the self-sufficiency of the local system. These solutions can, for example, reshape the demand curve to lower and smooth the peaks or shift some loads to exploit the renewable production, improving the coupling of demand and local energy production [10].

On the other hand, islands always had to face and overcome multiple complexities to access energy, even in developed countries. In these systems, energy security is still a matter of major importance due to the strong dependence on imported fossil fuels, being the energy price highly influenced by the fuel's cost: in fact, the oil price in islands can be 3 to 4 times higher than that in the mainland and, being almost completely dependent on it, the island economy may be affected [10]. For this reason, the integration of renewable energy sources in the island's power systems, or even the complete decarbonisation of the energy system coupled with an increase of technologies efficiency and reliability, could bring, in the long term, a higher level of energy security along with an overall cost reduction.

Consequently, in the perspective of a high renewables penetration or a renewable-based energy system, the energy storage technologies are a key factor for dealing with the volatile and stochastic behaviour of the renewable energy generation, and for its coupling with the demand, effectively shifting and flattening the power demand curve ([10], [11]). Some of the most popular, technology ready and frequently deployed storage energy systems are battery energy storage systems (BESS), compressed air energy storage (CAES) and pumped hydro energy storage (PHES).

Geographical islands are naturally microgrids working on islanded mode, being often used as case studies to test innovative energy models for the best solution on a technical, economic and environmental point of view. Their modelling and simulation are of capital importance since they help to design and shape the system in order to optimize its operations and increase the security of supply. In this perspective, as highlighted in [12], the forecasting of demand and of renewable production has crucial importance: an accurate forecast reduces the balancing needs and required reserve power, generally assured by fast-diesel backup or storage devices.

In fossil fuels-dominated systems the matching of energy demand and production follows consolidated techniques, where the outcomes are mostly dependent on energy market prices and generators' technical constraints due to their ability to accommodate rapid changes in the demand. With the increasing production of RES, new challenges are presented to the energy systems and their managers, both in the economical organization of the energy system, as in its long-term planning, and in the electrical grid operations. Therefore, new approaches are then needed to model these evolving systems.

Modelling tools can support grid managers in the everyday decision-making, by optimizing the operating conditions, but also by providing policymakers and investors, evidence of suitability in the long-run, thus helping to take planning and investment decisions.

The Vulcano modelling tool, built during the last ten years at IST, has this purpose, albeit it was initially created to reproduce the energy system of the Azores islands, and therefore it needed further developments to achieve this goal. Several improvements were made to make it more generalized and user-friendly tool than it was at the beginning, but its evolution is still underway. Past simulations have shown that it can thoroughly reproduce the existent energy system [13], even better than some of the most used commercial tools [14]. However, the energy systems are changing, and along with the increase of production from renewable energy sources, storage systems are being integrated. Due to the increasing role of energy storage in the dispatch and regulation of power, the simulation of its behaviour and operation is of utmost importance. Moreover, every system has its own characteristics and requirements, so the tool needs to be more flexible and able to reproduce different criteria and constraints if has to become versatile and suitable for a large number of different types of systems.

1.2. Research hypothesis and objectives

The main objective of this thesis is to provide a more informed insight on if modelling tools and economic dispatch optimization algorithms are capable of assertively model energy systems with high RES penetration and storage capacities, especially on islanded systems as geographical islands. The main questions to be addressed are the following:

- Are self-built modelling tools versatile enough to model a diverse range of energy systems?
- How should modelling tools adapt to operate with high RES penetration, without compromising grid stability?
- Is storage capacity modelled in a realistic way and how its operation can be optimized?

To help gather the answers for these questions, the first step was to verify and validate the Vulcano tool operations, to understand if it could effectively perform the modelling and simulation of different types of energy systems. This action was pursued comparing its results with the ones of the commercial software HOMER. Then a literature review on modelling tools algorithms and storage integration algorithms was performed. Vulcano tool was thoroughly analysed both in the code structure and in the results provided by the first simulation; once the problems were identified, some solutions were studied and proposed. All the improvements made to the code were checked with new simulations to verify the effectiveness of the modifications. For the simulations of the energy systems, two islands of Portugal have been considered: Terceira, of the Azores archipelago, and Madeira Island.

1.3. Thesis' Structure

The thesis is organized as follows:

- Section 2 contains the literature review of the different categories of modelling tools existing and of the two tools considered; further, a literature review of different models for the integration of storage operation in the unit commitment problem is presented;
- Section 3 details the two modelling tools used, their features, flaws and differences;
- Section 4 explains the methodology adopted to pursue the analysis, simulations and modelling improvements;
- Section 5 presents the first set of Vulcano validation against commercially available tool, HOMER, for Terceira island power system, performing parallel simulations from the

two tools, to highlight the differences and decide which aspects of the Vulcano tool were to be improved;

- Section 6 focus on the analysis of the problems found and the solutions adopted in Vulcano tool to improve the modelling and storage operations;
- Section 7 reports the application of the improved tool to a different case study (Madeira Island); and
- Section 8 states the final conclusions and future work.

2 Literature Review

2.1. Modelling tools

With the growth of renewable energies and microgrid systems, energy systems' modelling tools have become popular, especially when dealing with the integration of renewable energy sources [15].

As described in [16], modelling tools analysis differ according to the spatial resolution (microgrid, cities, regions, countries-wide) and temporal resolution (minutes to decades), and can be classified in four categories: macro-economic models, energy systems planning models, energy system balance models, grid operation and dispatch models (Figure 1). The scope of the modelling tool can also be different: in fact, there are tools that simply simulate an energy system, tools that provide different scenarios, or tools that perform a system optimization. Hybrid tools integrate the capabilities of different types of tools to respond to the increasing complexity required for modelling the evolution of existing energy systems. In particular, the two functions that are mostly needed to combine are the short-term optimization, which is usually on an hourly time scale, and the multi-year optimization as a support tool to make investment planning decisions.

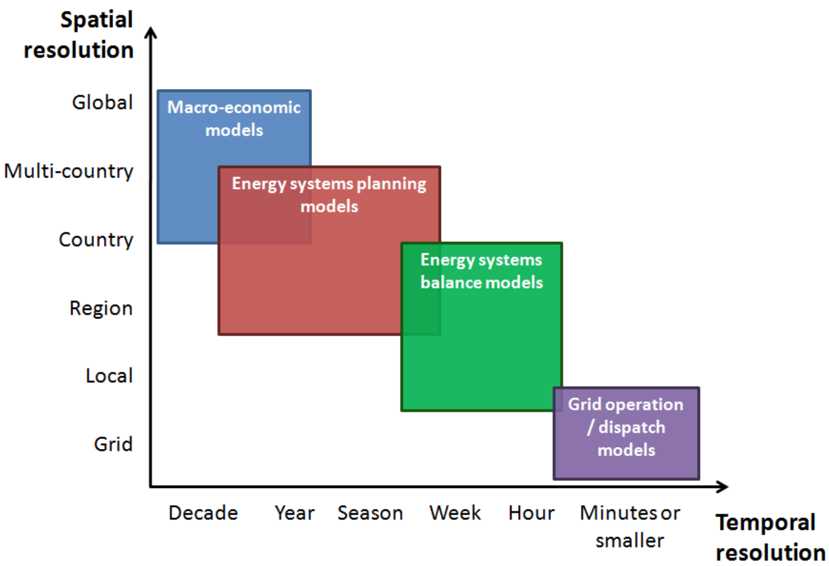


Figure 1 – Scheme of modelling tools categories

To model an energy system, the first step is to choose a modelling tool, and in order to do so the time horizon and time step of the model, and the scale and the frontiers of the system need to be defined. The system has to be further characterized in terms of energy supply available technologies, demand and future scenarios (if needed). The model will then integrate and match supply and demand curves [16]. Additionally, some smart grid mechanisms can be used to best match supply and demand as energy storage, demand response or RES forecasting.

The modelling of the systems becomes particularly important in the case of isolated microgrid systems. In particular, in the short-term optimization applied to microgrids systems, the importance of the unit commitment (UC) problem is growing with the constantly varying demands [17]. UC is an optimization problem that aims at determining the operation schedule of the generating units at every hour interval with varying loads under different constraints and environments. Many solutions have been proposed for the optimization of the UC problem; these can be classified based on the type of problem, on the constraints used in the problem, on the optimization function chosen, and on the algorithm [17]. As such, the UC problem can be approached as a deterministic or stochastic problem depending on the knowledge of the load and of renewable availability, but also on the solution needed. Moreover, solution techniques can be classified into conventional techniques, non-conventional techniques and hybrid algorithms. Conventional techniques include exhaustive enumeration, priority listing, dynamic programming, branch and bound, integer programming, simulated annealing, Lagrangian relaxation, tabu search, and interior point optimization. Two of the most common techniques are Mixed Integer Linear Programming (which is an integer programming conventional technique) and Genetic Algorithms (a non-conventional technique), which are preferred for their high-efficiency flexibility and general applicability. Looking at the literature, it can be found that almost all standard solution techniques for the classical UC problem have been further developed and partially adapted to the microgrid application [18].

HOMER is one of the most used tools to model a microgrid energy systems and in general to analyse the integration of renewable energy into various energy systems [15]. On the other hand, Vulcano tool, is an academic model developed at Instituto Superior Técnico (IST), by [19], [20], [21], [22], targeting the modelling of isolated microgrids, with a fair share of renewables, having been tested for modelling the islands of Corvo and Terceira (in the Azores archipelago), and Madeira. With the development of a friendly Graphic User Interface (GUI) in [22], Vulcano tool has now reached a stage of development where there is the need to internally validate it thoroughly, confronting its results with the ones of commercial and consolidated software, like HOMER.

Although Vulcano, in its early development stage, was already confronted with EnergyPLAN and HOMER, the comparison focused on the Demand Response function [14], demonstrating that Vulcano was more capable of reproducing some real operation behaviour of the system with respect to the other two software.

Both HOMER and Vulcano modelling and features will be further detailed and analysed in Section 3.

2.2. Storage

Energy storage systems (ESS) are of fundamental importance in the implementation of microgrid hybrid systems, being Pumped Hydro Energy Storage (PHES) and Battery Energy Storage Systems (BESS) the most used in its deployment [8]. BESS are a typical choice for power flow regulation in micro-grids and are often used to smooth power peaks [23], while PHES are frequently viewed as the most promising technology to increase renewable energy penetration levels in power systems and particularly in small autonomous island grids with abundance of water resource, where they are mainly used for peak load shaving. These systems represent the most commercially important means of large-scale energy storage [24]. Thus the two systems are normally chosen in HRES deployment due to their different characteristics in terms of power and energy density, typical size and time scales which allows to address different storage purposes [25], [21].

Different methods can be found in literature for the unit commitment of the storage capacity in a microgrid model. In [26] a stochastic method for the unit commitment is used, where the objective function minimizes the overall production cost and considers two main components: the energy cost which includes start-up costs of the generators and fuel costs, and reserve costs that reflects the effect of generating less power than the available by the generator. The power of the storage unit can assume both positive and negative values, where the positive indicates a discharge operation, while the negative indicates a charge operation. Following the unit commitment problem, a new optimization problem for the economic dispatch is performed with the same constraints. In [11], battery charge/discharge activities are determined by repeatedly solving a linear optimization problem over a moving control time window. The controller essentially determines the rates by which the battery should be charged or discharged; it employs a 24-hour ahead prediction window of net demand power vector and electricity prices to make optimal battery charge/discharge decisions at each time-step. The goal is to minimize the cost of electricity, ensure smoothness of the power profile at the point of common coupling to the grid, reduce battery operating cost while supplying the user power demand. In the cost function associated, the use of the battery is penalized when the energy level of the battery is low because any reduction of the residual capacity of battery below a certain limit degrades the battery performance and reduces its lifetime. The penalization cost can also be found in [27] where a battery usage cost in the optimization is employed to avoid unnecessary battery activity. These two studies refer to grid-connected systems. In [28], the storage is charged and discharged following a schedule calculated on the basis of the wind and solar forecast on a day-ahead level, updated in real-time operation: by frequently rescheduling the energy injection/withdrawal schedule of storage, the real-time injection/withdrawal of energy is optimally determined in anticipation of extended forecast conditions. Moreover, in this model the operating costs of the system include, along fuel, CO_2 and start-up costs, a wind curtailment cost and a load shedding cost, but there is no cost associated to the use of storage units, since, according to the authors, this would only make sense to retain an efficient energy level of the storage assets, reflect the charge and discharge efficiency rate of storage or avoid intensive use of storage. In [29] the renewable production is stored only if it is higher than the demand; the condition for the decision of charge/discharge the storage is based on the State of Charge (SoC) of the battery. In [30] a cooperative strategy between diesel generator and battery energy storage system is considered; the objective is, also in this case, to minimize the overall cost of the system which consists of depreciation cost, operation cost, pollutant emission cost, and economic subsidies for renewable energy sources. The excess of energy produced is calculated with respect to the minimum economic power output; if there is excess energy and the SoC of the BESS is not the max, then the BESS will be charged, otherwise, the wind will be curtailed. The battery is discharged only if the SoC of the battery is over the minimum value and if the diesel generator is not able to meet the load independently. In [31], before performing the dispatch, a peak-cutting limit and a valley-filling limit are set; this is applied in a case of a grid-connected systems, where the power supply load is considered as the load minus the distributed generation production. The limits will be used as criteria for the charging and discharging operations: when the power supply load is greater than the peak-cutting line the discharge occurs and when the power supply load of the upper power grid is less than the value of the valley-filling line, the charging will occur. In this case, the criteria are used to optimize the coupling between the upper grid and the distribution network, to exploit the distributed generation production and avoid overload of the transformer. The priority list method applied to the unit commitment problem can be found also in [32], where the status of the storage (which in this case is a superconducting magnets energy storage system) is decided prior to the creation of the priority listing, considering the peak and off-peak demand. The load demand is then adjusted based on the charging and discharging status and then the priority list is generated. The adjustment of load demand can also be found in [33] where the curve is modified at each hour in order to avoid curtailment, implementing cost penalties for load not met and wind curtailment.

In conclusion, in most of the cases analysed the output of the dispatch was a value for the storage that could be positive or negative. In some cases, the decision to charge or discharge was made *a priori* only looking at the demand profile, therefore creating a schedule to follow in the dispatch. In every case, though, a different optimization algorithm was used; moreover, it could not be found another example where the integration of an ESS was performed while using a priority list method. In more than one case, alternative solutions that would not modify the dispatch algorithm, but that could impact the storage operations were found, as the assignment of a cost for wind curtailment or an additional constraint for the charge and discharge. The implementation of these solutions will be further explained and analysed in Section 6.

3 Modelling tools

3.1. HOMER Pro

HOMER Pro is a software for technical-economic optimization of microgrids, remote utilities and distributed generation systems of all sizes of the software company HOMER Energy [34].

HOMER is a modelling and planning tool, so it considers both the operational costs and the investment and replacement costs, which are needed to evaluate the economic convenience of a certain solution. Its optimization is, in fact, performed based on the Net Present Cost (NPC): "*The total NPC is HOMER's main economic output, the value by which it ranks all system configurations in the optimization results, and the basis from which it calculates the total annualized cost and the levelized cost of energy*" [35]. Thus, the costs include capital costs, replacement costs, Operation & Maintenance (O&M) costs, fuel costs, emissions penalties, while revenues include salvage value.

The dispatch can be done with different methods: Load following, Cycle charging, Combined Dispatch or Generator Order. Under the Load Following strategy, HOMER dispatches the system's controllable power sources to serve the load at the least total cost at each time step; under the Cycle Charging strategy, whenever a generator is required, it operates at full capacity, and surplus power charges the battery bank; Combined Dispatch is a combination of the previous two strategies; Under the Generator Order strategy, HOMER follows a defined order of generator combinations, and uses the first combination in the list that meets the demand. [35]

To optimize the size of the power system, there are two types of optimization possibilities. The first is the *Search Space* that will simulate all of the feasible configurations in the system and determine the most efficient configuration within the range of the component input values decided by the user, i.e. between a range of generators sizes. The second is *HOMER Optimizer*, which will automatically find the optimal size or quantity, within the lower and upper boundaries that the user has to input. [35].

Generating capacity in HOMER can be modelled for a set of predefined technologies, choosing the types of generators from a catalogue provided by the software, or customizing them, however, with some constraints and limitations.

For wind, hydro and solar plants, a resource input is needed: in the resource section, the renewable resource availability data can be manually inserted or directly downloaded from the NASA Surface meteorology and Solar Energy database. The data of Global Horizontal Irradiation (GHI) and wind speed are averaged values over, respectively, 22- and 10-year period, while for the hydro resource there is no possibility of data download since it is strongly dependent on the precise localization and the type of the specific plant.

However, the only renewable thermal generators that HOMER considers are the biomass-fuelled ones, leaving out the possibility to accurately model residual solid waste or geothermal generators, which however can be done if considered as standard thermal generators, changing the fuel characteristics and the specific emissions.

The software models a system with a time span of one year and time-steps of 1 hour, with the possibility of choosing the minutes per time step, from 1 to 60. Multi-year simulations are also available.

One of the limitations of HOMER is that there is no possibility to insert the start-up or shut-down costs for the generators. There is also no possibility of limiting renewables, although a warning can be set when the overall renewable percentage exceeds a certain limit. There is, on the other hand, the possibility to input a minimum percentage of renewable production.

3.2. Vulcano

3.2.1. History

The Vulcano tool has been first developed 10 years ago, in the year 2010, and since then it has been modified and improved multiple times. However suitable for academic and scientific purposes, it still has not reached a readiness level appropriate to be commercially available for microgrids operators and managers. The main drawbacks of Vulcano tool is lacking flexibility to adapt and reproduce other different types of energy systems. The tool was originally developed in MATLAB by Abeysekera M. [19] in his Master Thesis, with the purpose of modelling the energy system of Corvo Island, in the Azores, where the majority of the energy was (and still is) produced by thermal generators. The main objective of the tool at that time was to analyse the economic dispatch, solving the unit commitment problem, trying to find the optimization strategy that would best replicate the real data.

The economic dispatch consists in the optimization of operating costs of power generators while respecting technical constraints [21], such as:

- Output power between the limits of minimum and maximum rated power
- Spinning reserve
- Ramp up and ramp down rates
- Minimum up and down times of the generators.

The economic dispatch equation to be met at every time step is the following:

$$P_{load} + P_{loss} - \sum_{1}^{NG} P_i = 0 \tag{3.1}$$

Where P_{load} is the demand power of the system, P_{loss} are the transmission losses, P_i are the power outputs of the number of generators (*NG*). For small microgrids, the transmission losses are assumed to be zero for simplicity and because of their relatively low influence on the solution in the small systems analysed [21].

Thus, the only costs considered are the operating costs, related to fuel consumption: fuel cost, cold and hot start-up/shut-down costs, no-load cost and incremental heat rate cost. For renewable generators and energy storage systems an equivalent fuel cost is considered, although for renewables it is null. The overall cost of a system is calculated as:

$$Total\ cost = \sum_{t}^{NT} Hourlycost_t \tag{3.2}$$

$$Hourly\ cost = \sum_{i}^{NG} Production\ cost_i + \sum_{i}^{NG} StartupShutdown\ cost_i \tag{3.3}$$

$$Production\ cost = (Ginc * x_i + Gnlc) * Gfc \tag{3.4}$$

where NT is the number of time steps, t is the generic hour, NG is the number of generators, i is the generic generator, x is the committed power for the generator i, *Ginc* is the incremental heat rate cost, *Gnlc* is the no-load costs and *Gfc* is the fuel cost; equation (3.3) is referred to a single hour t and equation (3.4) is referred to a single generator i.

The software can model time horizons of one day or of a custom length (smaller or larger), with 1-hour time-steps. Long-term calculations are also available to analyse the system on a multi-year scale and to perform an economic feasibility evaluation.

The tool was successively improved by Neves, who first introduced the Demand Response function and its integration in the optimization of electricity dispatch in [20] and then the Multi-Day modelling in [12].

Further developments were made in two other master thesis: Guzzi [21] added the integration of the Energy Storage Systems, while Rita [22] developed a Graphic User Interface, adapting the tool also to Long-Term Calculations, receiving as inputs Investment and O&M costs.

In this thesis, the main focus will be on the integration of the ESS, while the Demand Response and the Long-Term Calculations functions will not be considered. Further, the GUI, which had been a significant improvement in the generalization of the code, was also improved and enriched with new features.

3.2.2. Modelling steps

As graphically described in Figure 2, Vulcano tool receives as inputs the technical parameters of generators, the renewable availability data, the demand profile and some user preferences for the analysis through the GUI, and returns as outputs the optimized dispatch, the shares of production per technology and the calculations of fuel consumption, production costs and CO_2 emissions. This is an exclusively modelling tool that bases its economic optimization only on the operational costs, considering which is the most economically convenient solution hour by hour, tracking the transition paths from one hour to the other, choosing in the end, the best path. The unit commitment problem uses a dynamic programming approach, with the optimization based on an economic dispatch model, and performed using the MatLab *fmincon* optimization function.

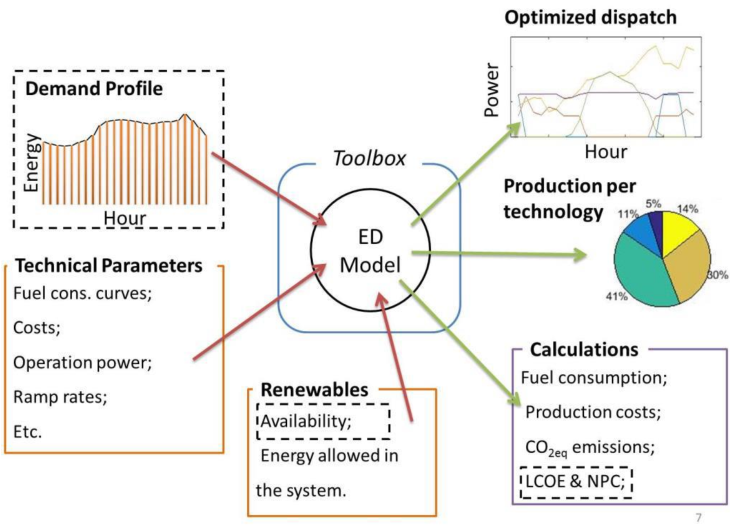


Figure 2 – Graphical description of Vulcano tool [22]

3.2.3. Code structure

To understand the functioning of the code, its problems and possible solution is important to know the structure of the code. Figure 3 presents the structure schematically.

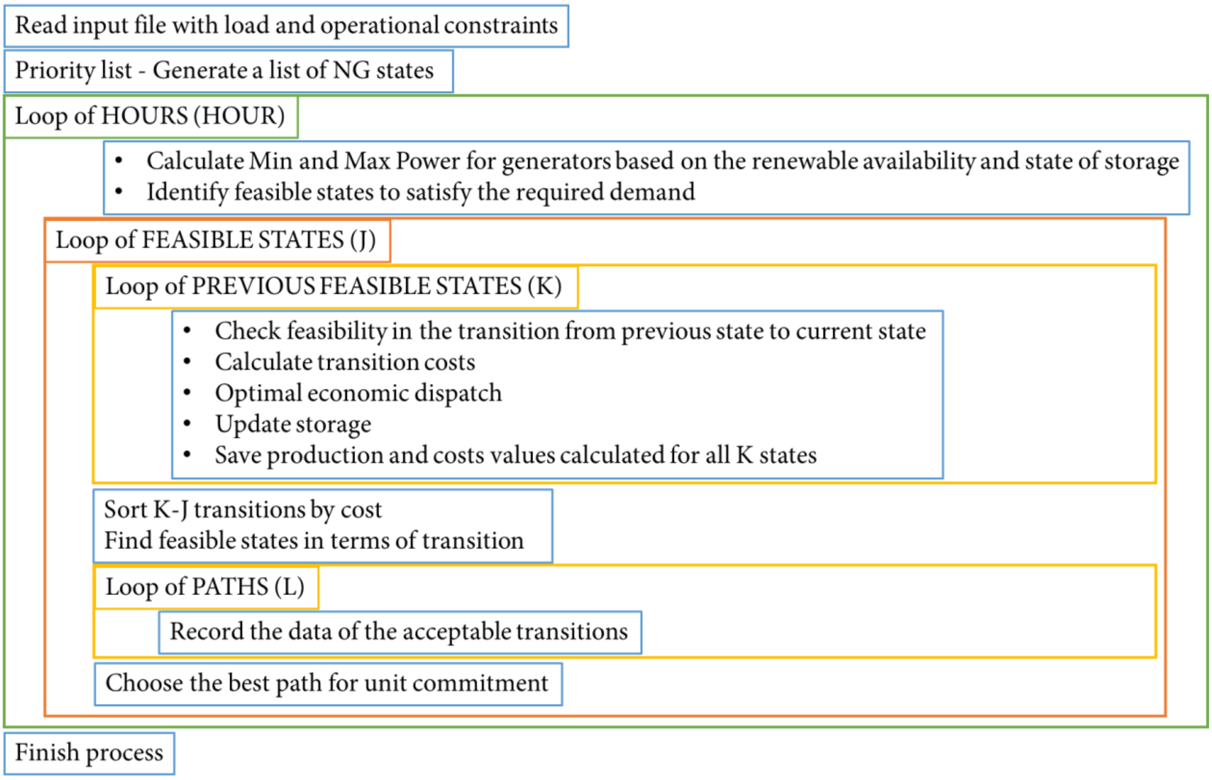


Figure 3 – Vulcano code structure (Modified from [20])

As seen in Figure 3, after receiving the inputs and creating a *List of States* of the generators' priorities to be considered in the commitment, for each hour, the states that can meet the demand and backup power requirements will be identified as *Feasible States*. Then each *Feasible State* will be confronted with the *Feasible States* of the previous hour, performing the dispatch and calculating the costs. At the end of the *Previous Feasible States* loop, a certain number of *Previous Feasible States* (equal to the *Number of Predecessors*) will be chosen for each current *Feasible State*. At the end of the *Feasible States* loop, a number of paths equal to the number of current *Feasible States* times the *Number of Predecessors* will be stored and considered for the next hour.

The *List of States* can be created in two ways: with the *Priority List* method or with the *Complete Enumeration* method. In the first case, the number of possible states is equal to the number of generators of the system: the generators are listed from the cheapest to the most expensive considering the maximum output of each, and each state will have an increasing number of generators which are added following the priority list. In the second case, all the possible combinations of generators are listed. Since the code was modified many times after its first development and, being the complete enumeration method too time-consuming, only the priority list was considered for the improvement of the tool.

3.2.4. Identified Problems

After an initial stage of getting to know the code and its functioning, some problems regarding the clarity of the code in terms of definition of variables and lack of comments were found. Moreover, the output results were only saved in a MATLAB data file. A function that would save an excel file with the hourly data of production, demand and renewable availability was created. However, after the harmonization of the code, further problems relating to the modelling features were encountered as detailed:

- Storage operations were not included in the optimization algorithm: although the storage had been previously inserted in the tool by Guzzi, it was still not considered in the optimization process. In fact, when entering the economic dispatch algorithm, the storage was considered as a generator, with a certain availability of energy depending on the state of charge and a certain availability of power that depends on the discharge rate of the type of storage. Thus, the storage can only operate in one mode, charge or discharge, so once the dispatch is concluded the storage is then updated:
    - If energy has been withdrawn from the storage, this means that it will be in discharge mode, so the energy content of the storage will be updated subtracting the energy used in the dispatch;
    - if the power of the storage in the dispatch is zero or lower than zero it will be charged with the energy excess from variable renewables. The quantity of energy that is stored will be the amount of energy that would be otherwise curtailed due to the limitation on renewable energy share allowed in the total dispatch.

  Thus, since the storage is considered in the generators list, it will always be checked first for discharging and then for charging.

- PHES was always charged before BESS since the charging does not follow a criteria of optimization, so the charging of PHES and BESS cannot happen simultaneously, but only one after the other;
- There can be only one entry for each type of storage; this is a lack of implementation that also derives from the previous problems.
- Renewables Data input: the tool is tuned to receive power output of renewables generation, i.e., after efficiencies. Thus, a possible improvement would be to calculate the power output for a given technology based on the renewables forecast (e.g. wind speed, solar irradiation, etc.);
- Listing methods: the complete enumeration function encountered several errors when trying to use it for multiday simulations.

3.3. Comparison

In Table 1, the main characteristics of the two software tools are summarized. As seen HOMER is more suitable to model a system with high renewable production, while Vulcano has a more detailed characterization of thermal generators. Moreover, being HOMER a commercial tool, it can perform a more detailed economic analysis as a support for investments decisions.

Table 1 – Comparison of Vulcano vs HOMER modelling tools

	Vulcano	**HOMER**
Time step	1 hour	1 hour or less
Simulation time span	1 day, customizable for longer periods	1 year
Dispatch	Economic Dispatch with Priority Listing, based on hourly operational costs	Based on NPC • Load following • Cycle charging • Combined dispatch • Generator order
Optimization function	*fmincon* MATLAB function	• HOMER Optimizer • Search Space
Possibility of long-term simulations	Yes	Yes
Operating constraints	- Minimum and maximum power outputs - Minimum up and down-time - Ramp-up and ramp-down rates - Spinning reserve - Maximum Variable Renewable Energy (VRE) fraction	- Operating reserve (as a percentage of load and as a percentage renewable output) - Maximum annual capacity shortage - Minimum renewable fraction
Thermal generators costs required	Fuel cost, cold and hot start-up cost, shut-down costs (acquisition, operating fixed and variable costs only in for long-term simulations)	Fuel cost, Capital cost, Replacement cost, O&M costs
Renewables and storage costs required	Equivalent fuel cost	Capital cost, Replacement cost, O&M costs

4 Methodology

The starting point of the work was to understand the tool operations and the code in detail with the help of manuals and previous projects. To better understand which aspects of the code should be preserved and which aspects should be improved, it was decided to compare the results of the tool with those of a commercial software; in light of the considerations done in subsection 2.1, the software chosen was HOMER Pro.

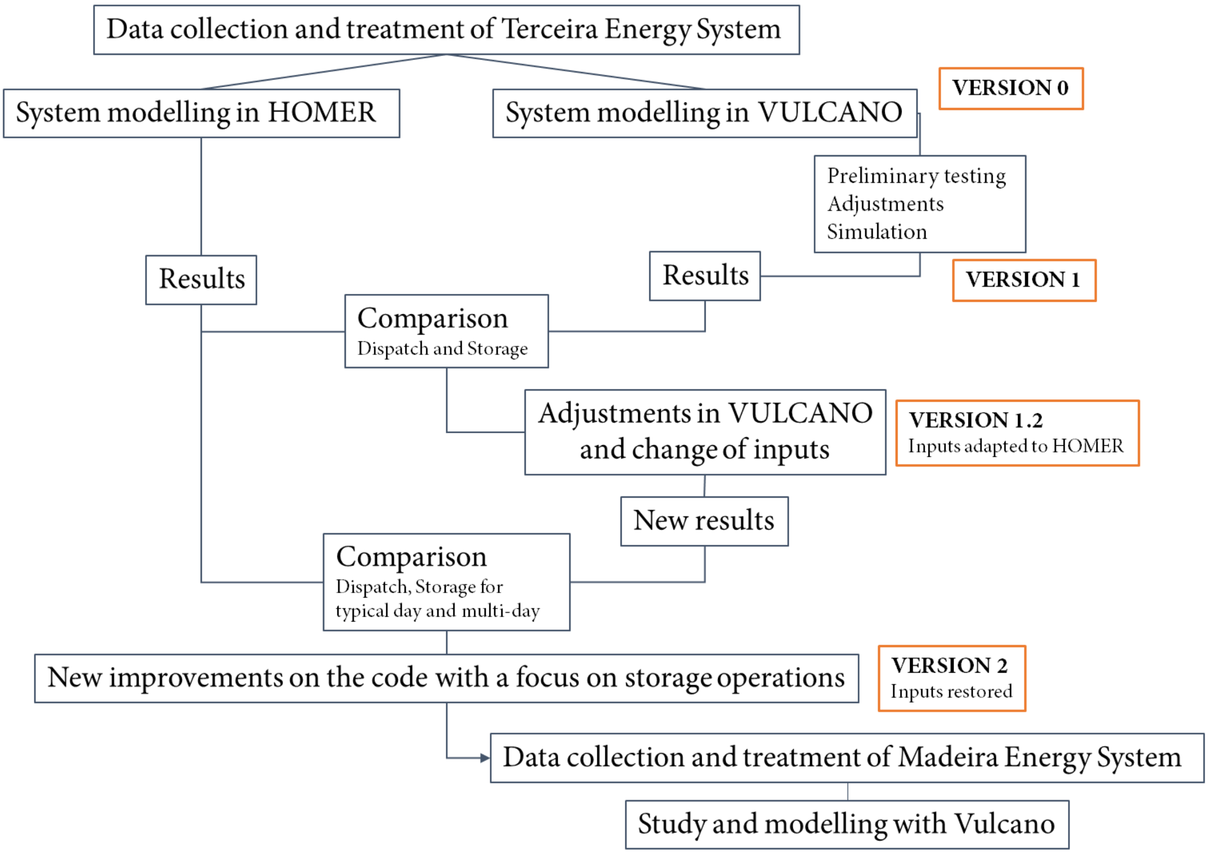


Figure 4 – Scheme of the work methodology

As shown in Figure 4, the comparison of Vulcano performance against HOMER was made modelling the Terceira island energy system with the input data initially collected by Guzzi F. [21], which was reorganized and modified according to the recent changes in the island's energy system. The first simulations were useful to correct some errors and a first comparison with the results of the simulation in HOMER was made (Version 1). Due to the structural differences of the two modelling software, a new set of simulations was made adjusting some input features of the Vulcano tool to make it behave in a more similar way to HOMER (Vulcano 1.2). With these new simulations, it was possible to make an even comparison between the results of the two simulations that allowed to identify and solve some conceptual problems of the Vulcano tool.

For the analysis, the "Typical Day Simulation" was used, albeit with this type of analysis was difficult to examine the behaviour of the storage. Thus, multi-day simulations were also made with the data of Terceira energy system and, although the results were similar, the behaviour of the storage was far from the one expected in real operation. For this reason, an analysis focused on storage operations was made to improve the Vulcano tool (Vulcano 2). This analysis consisted of identification of the problem, on a literature review of the algorithms for storage operations, and on the identification and implementation of possible solutions.

With the latest modifications on the code for storage operations, the energy system of Madeira was eventually simulated, considering two different years and two different configurations of the data set.

The user's manual, firstly developed by Rita [36], was improved with the code updates and advice for future guided work in the code.

4.1. Methodology for ESS integration

As stated in subsection 3.2.1, the ESS was integrated into the code by Guzzi F. [21]. The inspiration for the algorithm used in Vulcano was taken from [37], where the integration of the ESS in the dispatch was considered as a sub-optimization problem. In fact, the model searches first the solution for the economic dispatch without considering the ESS, and then the model runs a second time only for the best path found in the previous simulation considering the ESS for the charge and discharge operations.

Guzzi added two conditions for the discharge activities: the first was that the load of the current time step had to be higher than a fixed percentage of the system's total installed capacity: $P_{load_i} > x\%\ Capacity$, where the $x\%$ of the installed capacity was calculated as the sum of the baseload thermal generators over the total power installed. This was to ensure that the ESS would substitute the more expensive/peak load generators rather than the baseload ones. The second condition was applied to the minimum SoC of the storage.

Thus, in the first attempt to integrate the dispatch of ESS in the Vulcano tool it was assumed that the load satisfied by variable renewable energy sources would not be more than 50%, so the amount of energy available for the charging was the difference between 50% of the load and the available renewable generation forecast. In equations (4.1),(4.2) and (4.3), the charge operation, including the constraints to account the maximum charge rate are described:

$$if\ C_{sto}(t) < C_{sto\,max} \cap \begin{cases} C_{charge}(t) = min(E_{ren}(t) - 50\%C_{load}(t)) \\ C_{sto\,max} - C_{sto}(t-1)) * \eta_{charge}, & E_{ren}(t) > 50\%C_{load}(t) \\ C_{charge}(t) = 0, & E_{ren}(t) < 50\%C_{load}(t) \end{cases} \tag{4.1}$$

$$if\ C_{bat}(t) = C_{bat\,max} \rightarrow C_{charge}(t) = 0 \tag{4.2}$$

$$C_{charge}(t) \leq \partial C_{charge}(t) \tag{4.3}$$

where t is the current time instant, $C_{sto}(t)$ is the level of charge of the storage, $C_{sto\,max}$ is the maximum storage capacity, $C_{charge}(t)$ is the energy charged, $E_{ren}(t)$ is the renewable generation available to be committed, $C_{load}(t)$ is the load to be met, η_{charge} is the efficiency of charge and $\partial C_{charge}(t)$ is the charge rate of the storage technology; parameters refer to the current hour t.

Additionally, the discharge would only take place in the peak hours. Looking at the specific case of Terceira island, this was ensured imposing the constraint that at least 25% of the load should be assured by fossil fuel generators, which is described in the equations (4.4), (4.5) and (4.6) [38].

$$if\ C_{sto}(t) > C_{sto\,min} \cap \begin{cases} C_{discharge}(t) = min\ (C_{fossil}(t) - 25\%C_{load}(t) \\ C_{sto}(t-1) - C_{sto\,min,}) * \eta_{discharge}, & C_{load}(t) > C_{base\,gen}(t) \\ C_{discharge}(t) = 0, & C_{load}(t) \leq C_{base\,gen}(t) \end{cases} \tag{4.4}$$

$$if\ C_{bat}(t) = C_{bat\,min} \rightarrow C_{discharge}(t) = 0 \tag{4.5}$$

$$C_{discharge}(t) \leq \partial C_{discharge}(t) \tag{4.6}$$

where $C_{sto\,min}$ is the minimum storage capacity, $C_{discharge}(t)$ is the energy discharged, $C_{fossil}(t)$ is the energy supplied by fossil fuel generators, $C_{base\,gen}(t)$ is the capacity of the two base generators with the lower specific consumption that are responsible for baseload, $\eta_{discharge}$ is the efficiency of charge and $\partial C_{discharge}(t)$ is the discharge rate of the storage technology; parameters again refer to the current hour t.

However, in order to make the model more stable, realistic and adaptable to any power supply system, an improvement in the storage dispatch method was considered necessary. In particular, this was integrated in the initial best path searching phase and the discharging conditions were replaced by associating a cost to the energy dispatched by the ESS. It has to be taken into account that these decisions were made considering a system where the total production of thermal generators is constrained at every time step by a lower bound equal to 25 % of the current load [21].

The two conditions for the discharge operation, though, were not successfully implemented; in fact, in the first version of the code in possession at the beginning of this thesis project, the discharge of the storage was not regulated. The storage operations were improved throughout the different simulations, that were used to find new problems and solutions. In Figure 5 a scheme of the configurations of the storage used for the different simulations and of the improvements made to the code regarding the storage operations is displayed.

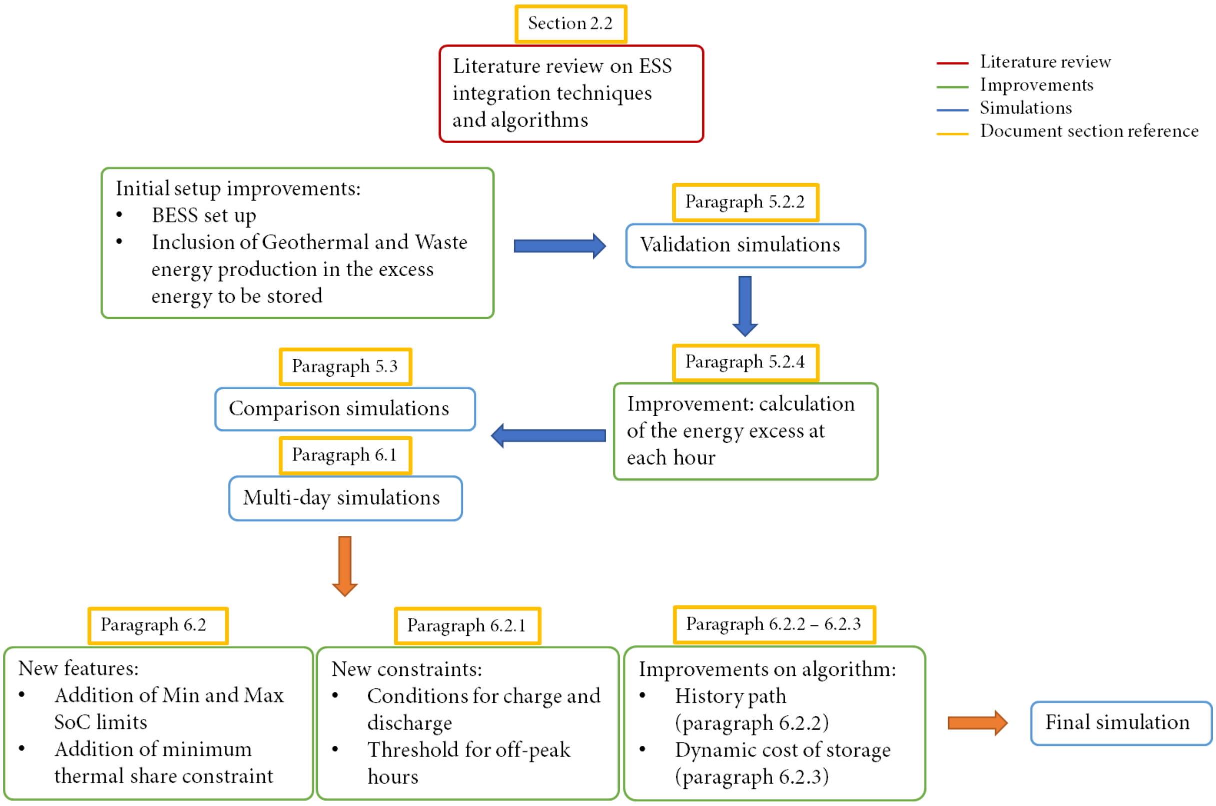


Figure 5 – Scheme of improvements for ESS integration

4.2. Error calculation

The error calculation is used as a control parameter to evaluate the distance between the Vulcano results and HOMER. The error calculation is not intended as a measure of how good Vulcano results are, but rather as a reference to a commercially available tool, as HOMER is. To compare the results of the simulations done with the two different tools in Section 5, the following error formulation has been used:

$$Error = \frac{|V_{HOMER} - V_{Vulcano}|}{V_{HOMER}} \tag{4.7}$$

where V is the generic value. To compare the dispatch, the error will be calculated on total daily values of energy produced by the different types of generators, on the total number of working hours. To compare storage operations, it will be calculated on different parameters as the average SoC of the ESS, the total daily energy stored and dispatched, and the peak value of energy content reached.

5 Modelling tools comparison

First, a set of simulations to deeply understand the two software tools and to find their main differences and inconsistencies between the two systems modelled have been done. Thus, to compare the Vulcano and HOMER tools, Terceira Island power system was modelled, using the same input data.

5.1. Case study: Terceira

Terceira is an island in the Azores archipelago, situated in the middle of the North Atlantic Ocean, with a total area of 402.2 km^2 and a population of 56,437 inhabitants. Terceira island is an active volcanic island, that is composed of several older extinct volcanoes and is crossed by the Terceira rift. The main economic activity on the island is raising of livestock and the production of dairy-based products. The climate is very mild, being influenced by its distance from the continents and by the passing Gulf Stream. Due to the marine influence, temperatures remain mild year-round [39]. Figure 6 shows the energy consumption for different sectors in the Azores region.

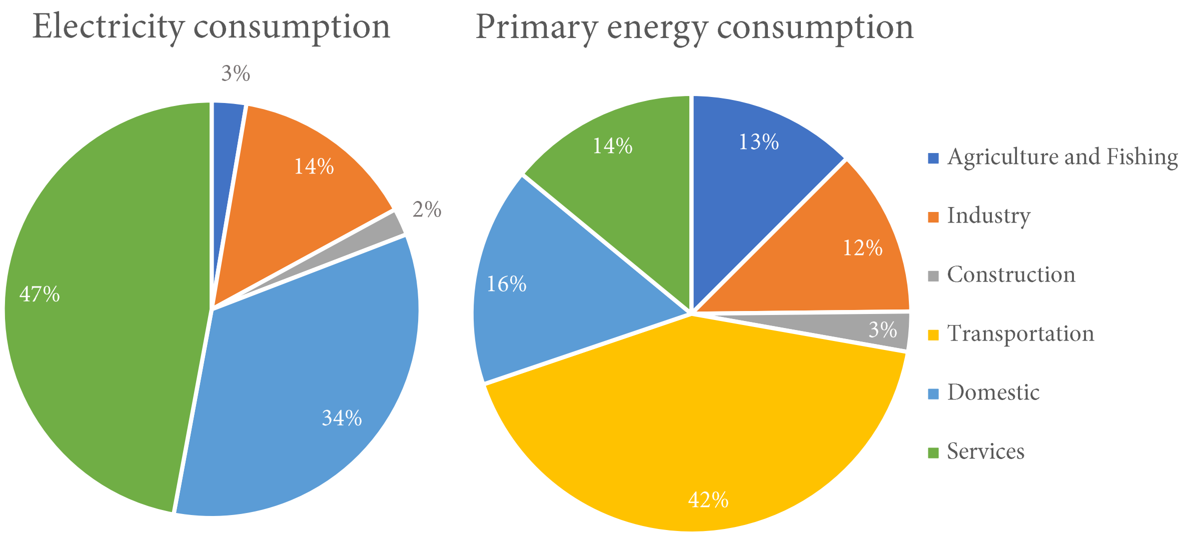


Figure 6 – Electricity and primary energy consumption by sector, 2016 [40]

Terceira energy system has been thoroughly described in F. Guzzi's master thesis [21]. Analysing the 2016 data shown in Figure 6, the largest share of primary energy consumption can still be attributed to transportation, while the Domestic and Services sectors account for more than 80% of the electricity consumption. The dataset obtained from [21] reports the collected and organized real data operation from 2013. However, the recent deployment of Geothermal and Residual Solid Waste (RSW) power plants, that entered in operation in 2016, justified the addition to the model of these two technologies.

The power system of Terceira consists of 10 Thermal Generators, 3 Hydro Generators, 2 Wind Farms, 1 Residual Solid Waste Power Plant and 1 Geothermal Power Plant as shown in Figure 7. Additionally, 1 Pumped Hydro Storage and 1 Battery Storage were modelled to see how the system operation would be influenced by storage systems, as a possible solution to assure grid stability and renewables efficiency. The complete and detailed plants list can be found in the annexes.

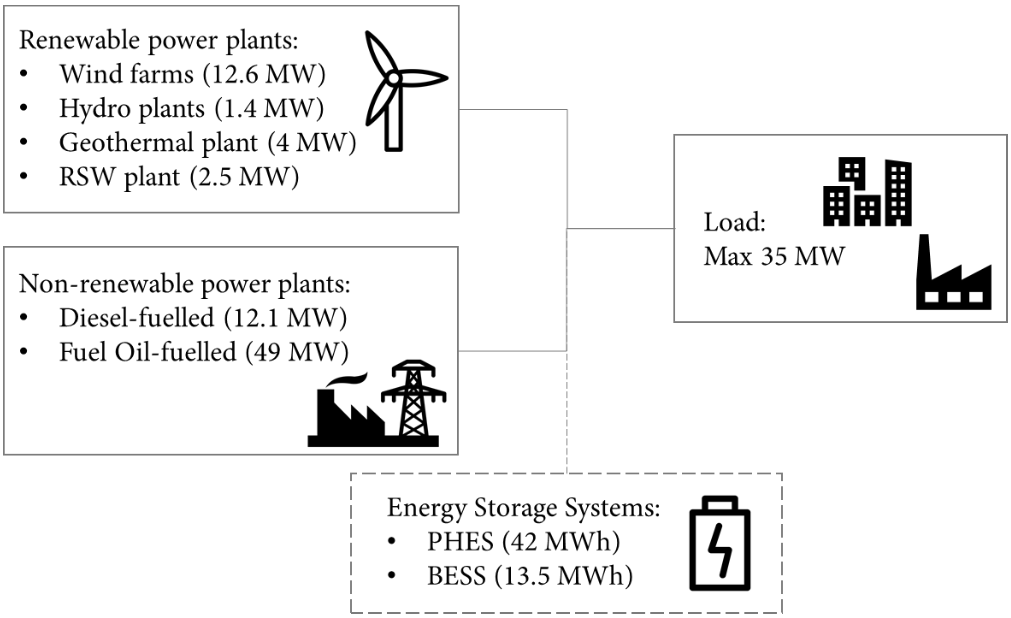


Figure 7 – Terceira energy system

The data of the Terceira power plants and other values needed as inputs have been obtained from [21], [41], [42], [43], [44].

The load profile for two typical days in March and October can be found in Figure 8.

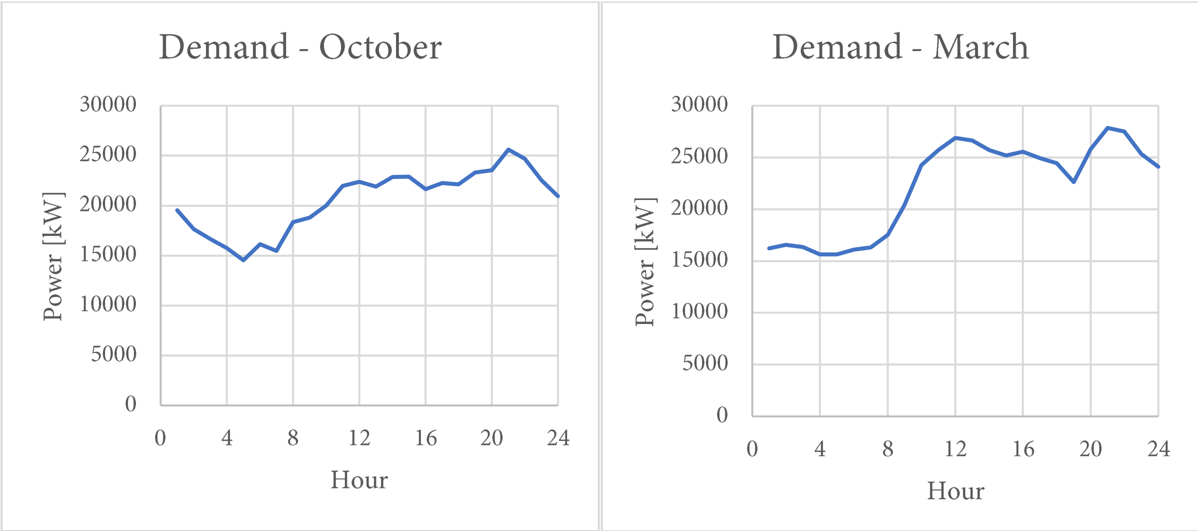


Figure 8 – Typical profile loads for Terceira in October and March

5.2. Validation

5.2.1. Inputs

Initially, the modelling analysis has been carried out only for one typical day with high renewable availability and with low demand (Sunday), although in this system there is only wind as a renewable variable resource. The 19th of January was chosen, corresponding to both the criteria.

For the RSW power plant, the resource is residual solid waste, which is always available if the rate of consumption of the power plant is lower than the rate of production of waste. In the Azores islands, the RSW power plants represent not only a source of electricity but also a wise solution to deal with the waste that should otherwise be exported with associated costs. Since Terceira receives the waste from the smaller western islands of the archipelago and given that this is the only RSW power plant in the Azores [45], this source can be considered as always available.

Regarding the geothermal, Azores having a volcanic origin and still reporting high activity assures that geothermal resource is also stable.

Hydro resource is also assumed as always available. There are three Hydro Power Plants on Terceira, but in both tools are modelled as one unified plant.

Thus, these power plants could work at constant and maximum power, which would represent a renewable base-load: geothermal and hydro are classified as 100% RES, while waste is classified as a 50% Renewable.

In HOMER the Load Following strategy was chosen while the *Search Space* technique was used for the optimization.

Table 2 presents a resume of the inputs for both Vulcano and HOMER.

Table 2 – Vulcano and HOMER inputs

		Vulcano	***HOMER***
Renewables	Renewable availability	Renewable power output from HOMER (after technology efficiencies)	Calculated from NASA data
	Renewable share	Wind, Solar, Hydro, Geothermal and Waste accounted as renewables	Geothermal and Waste do not account as renewables
	VRE% allowed	Yes, 50% including all types of energy sources that are stored	No, only a warning
	Geothermal, Waste, Hydro modelling	Subjected to optimization, and modelled as one big power plant per technology	Always committed at nominal capacity, and modelled as one big power plant per technology
Storage	Origin of Energy stored	Wind, Solar, Geothermal, Waste	Wind, Solar
Costs	Investment, O&M, replacement costs	Zero	Zero
	Renewable costs	Zero, priority defined with the priority listing	Zero
	Input cost for storage	LCRES calculated	Investment, O&M costs

5.2.2. Modelling dispatch comparison

Simulation results from the two models report very different behaviours, as shown in Figure 9.

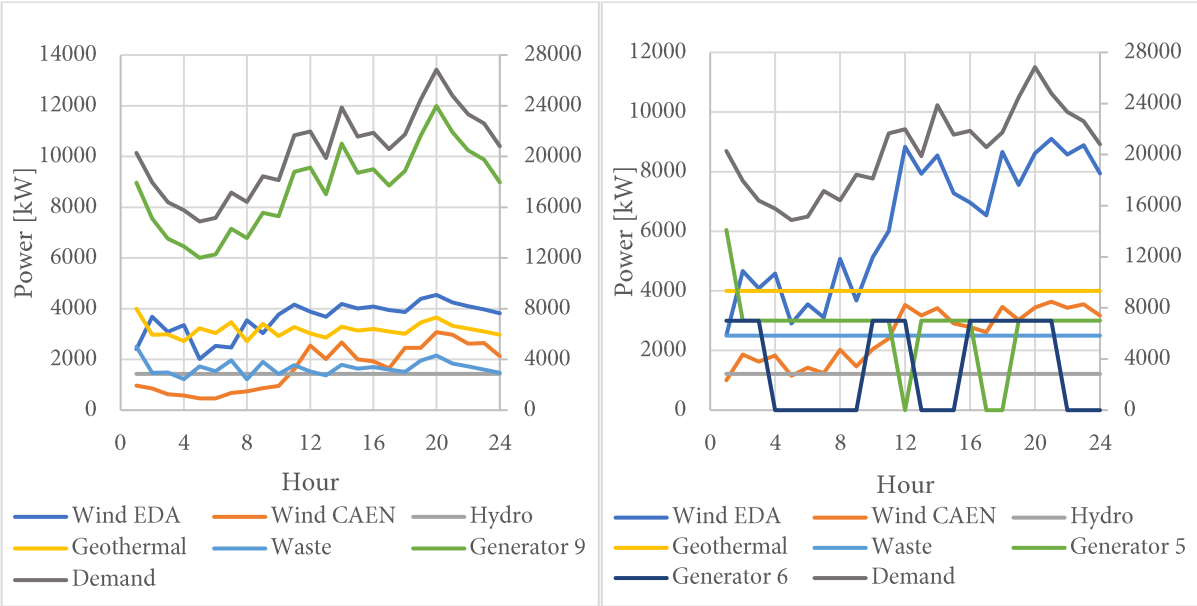


Figure 9 – Results of the dispatch simulation in Vulcano (left) and HOMER (right)

In the dispatch, Vulcano tool (Figure 9 left) reports one of the big-size generators (12300 kW) always in on-state, and following the load demand, while in HOMER (Figure 9 right) the thermal generators' dispatch is done with two medium-size generators (6100 kW) which are used at minimum power and are turned on-off to cover peaks and adjust to the demand. In a first analysis, this could be explained by the fact that in HOMER there are no start-up or shut-down costs so there is no penalization on turning on and off the generators.

Table 3 shows the distance in energy production and working hours between the results of the two tools. It has to be considered that in HOMER's results the wind energy production includes also the energy that will be stored, but the error on the effective cumulative wind production is still 33.3%. For all renewable generators, the difference is not negligible, proving that with this configuration the results of the modelled system are too far from each other to be effectively compared.

The fact that in HOMER the wind power in the dispatch is higher than in Vulcano, can be explained by the presence of limitation on the renewable production in Vulcano, which, instead is absent in HOMER where there is only a warning if a certain limit of renewable penetration is exceeded, which however will not prevent the use of the wind energy in the dispatch. The difference for Geothermal and Waste Power Plants is due to the way the parameters of maximum and minimum power were defined as inputs: in fact, while in Vulcano the minimum power was 0, in HOMER, it was defined only the possibility to have the generator on at maximum power.

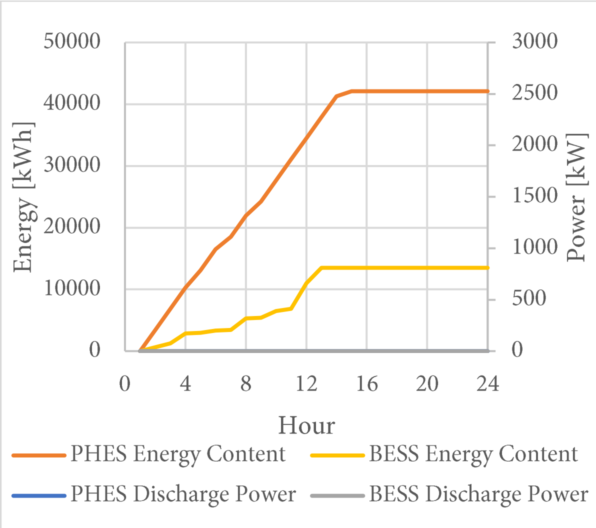
Table 3 – Error on energy production and working hours

		Fuel Oil	Wind	Hydro	Geothermal	Waste
Error [%]	Energy production	105.0	39.9	17.6	20.7	33.1
	Working hours	15.3	0.0	0.0	0.0	0.0

Regarding the storage (Figure 10 and Table 4), the PHES is charged in both cases, but while in Vulcano is charged up to the maximum capacity along with the BESS, in HOMER is charged only up to the 14% of the total capacity; this also happens because in HOMER all the renewables can be used in the dispatch. Moreover, in HOMER the energy stored is also used in the dispatch, while in Vulcano it is never used. The great difference in the quantity of energy stored is because in Vulcano geothermal and waste energy in excess are stored along with VRE, and to the fact that VRE is limited in Vulcano and not in HOMER.

Table 4 – Error on PHES parameters

		Vulcano	**Homer**	**Error [%]**
PHES	Energy stored [kWh]	42100	19792	112.7
	Energy dispatched [kWh]	0.0	9690	100
	Average SoC [%]	70.1	9.3	656.1
	Peak of energy content [kWh]	42100	5868	617.4



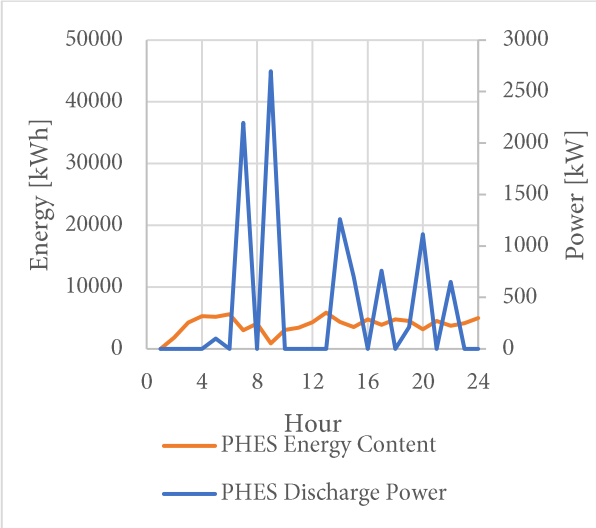


Figure 10 – Results of storage operations simulation in Vulcano (left) and HOMER (right)

Renewable penetration in HOMER is calculated as the production from Wind, Solar and Hydro (including the energy that can be stored) over the Total Electrical Load Served; in Vulcano, it is calculated as the production of Wind, Solar, Geothermal and Waste (excluding the energy that is stored) over the Demand. With these formulations, the renewable penetration is 48.6 % for HOMER and 49.9 % for Vulcano.

Because the two software calculate this factor in two different ways, a new formulation is proposed to confront the values: the renewable penetration will be calculated as the production of renewable energy in the dispatch (excluding the energy that will be stored), including Wind, Solar, Hydro; in alternative it can be calculated also considering Geothermal and Waste. The values in Table 5 show again that the renewable penetration in HOMER is much higher than in Vulcano.

Table 5 – Renewable penetration

	Vulcano	***HOMER***
Not including Geothermal and Waste	32.87%	48.59%
Including Geothermal and Waste	57.20%	77.12%

The overall cost of the system is higher for Vulcano than for HOMER since more Fuel Oil is used, while emissions are 10% lower (Table 6).

Table 6 – CO_2 emissions, total cost and fuel consumption

	HOMER	***Vulcano***	***Error [%]***
CO_2 Emissions [kg]	166031.2	149373.7	10.0
Total Cost [€]	15097.8	28596.5	89.4
Fuel Consumption (Fuel Oil) [L]	23981.0	52173.9	117.6

The results of this first simulations show that the tools in principle have very different behaviours: in fact, HOMER does not curtail renewables and maximizes their share in the dispatch, adapting the committed power of thermal generators, while Vulcano uses thermal generators for load following and adapts the production of the other renewable sources, sometimes curtailing renewables. Therefore, to make an even comparison, new simulations with different inputs were needed, which were carried out in section 5.3.

5.2.3. Problem in Vulcano code

To further analyse the balance between renewable energy in the dispatch and energy stored, a new output plot has been added to the tool. Thus, Figure 11 reports the renewables dispatch for January 19th, respectively for the case with VRE factor equal to 20% and to 100%, where:

- *Renewables Allowed* is the maximum power of the load that can be satisfied with production from VRE;
- *Renewables Availability* is the maximum renewable power that could be produced with the available resources;
- *Renewables Production* is the effective renewable power committed in the dispatch;
- *Energy Stored* is the renewable energy not committed and hence stored; and,
- *Energy Curtailed* is the renewable energy which is not committed neither stored.

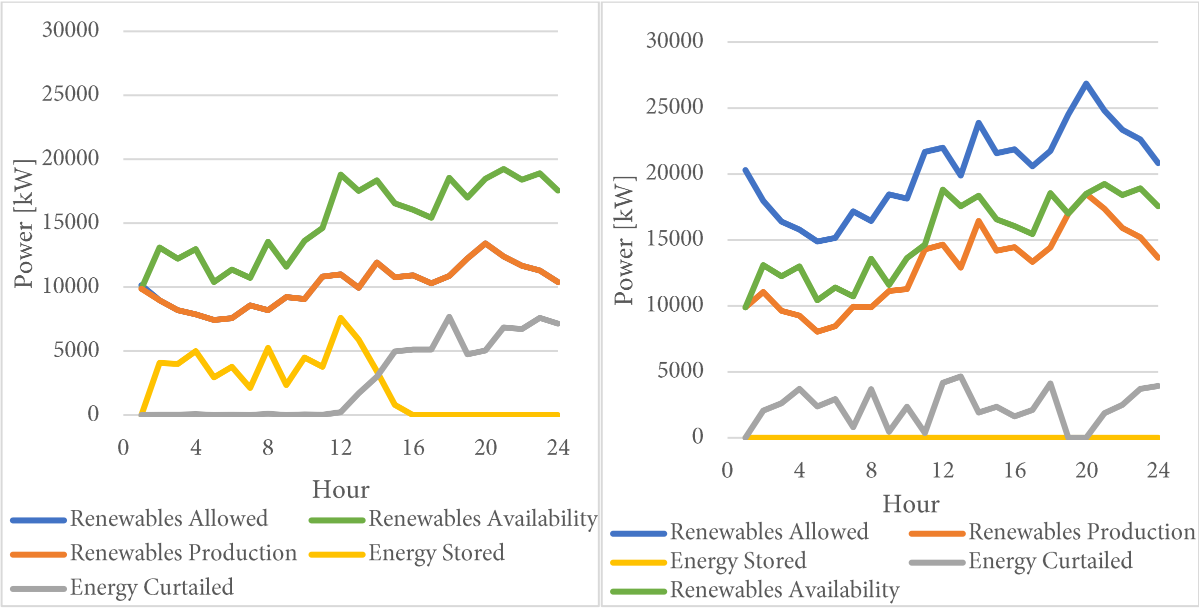


Figure 11 – Renewable balance for January 19th with VRE limit = 20% (left) and VRE limit = 100% (right)

It can be noted that the renewable energy produced is at the maximum possible (in fact the orange curve corresponds to the blue one in Figure 11 left), while energy is initially stored and when the two storage systems are full, it will be curtailed. Nevertheless, Figure 11 right, shows a situation without limits on the renewables allowed (VRE factor = 100%). It can be noticed that even though the energy that could be produced from renewables (*Renewables Availability*, green curve) is lower than the one that would be allowed (blue curve), the actual production (in the dispatch, orange curve) is even lower. This happens because of constraints on the generators that can win over the maximization of renewables. What strikes the attention, though, is that the energy that is not used in the dispatch should be stored (yellow curve), but instead, it is curtailed (grey curve). Reviewing the code, it was found that the quantity of energy that has to be stored hour by hour was calculated at the beginning, before the dispatch optimization, based on the excess of available renewable energy, which exceeded the renewable energy allowed in the dispatch. Consequently, the energy that was not used in the dispatch (difference between green and orange curve) was not considered for the storage, leading to zero energy stored.

To check this behaviour, simulations with larger storage were also run. In the model with a low percentage of VRE allowed in the dispatch, the larger storage allowed to avoid curtailment, while in the model with no limit on the VRE penetration factor, the energy stored was lower, as most of the VRE was directly dispatched.

5.2.4. Edits to Vulcano code

In light of the problems and disparities shown in the previous chapters, two major modifications have been made to the code:

- The first had the objective to exclude the Geothermal and Waste energy from the constraint of VRE percentage allowed, while still considering these two technologies for the storage;
- The second aimed at calculating the quantity of energy to be stored hour by hour in the loop (and not at the beginning as in the initial version of the code).

One more problem found in the code was in the process of charging, more specifically in the update of the variable containing the energy to be stored. After the economic dispatch, the storage availability is updated first for the PHES and subsequently for the BESS; the quantity of excess energy to be stored is memorized in only one variable which, after charging the PHES, has to be updated with the quantity of energy left that will charge the BESS. The quantity subtracted from the variable was only the one that is actually charged in the PHES, but it was not considered that some of the energy is lost in the process of charging, due to the charging and discharging efficiencies. As a result, the quantity of energy left to be charged in the BESS was higher than the real one. The balance that considers this quantity of "lost" energy can be seen in Figure 12.

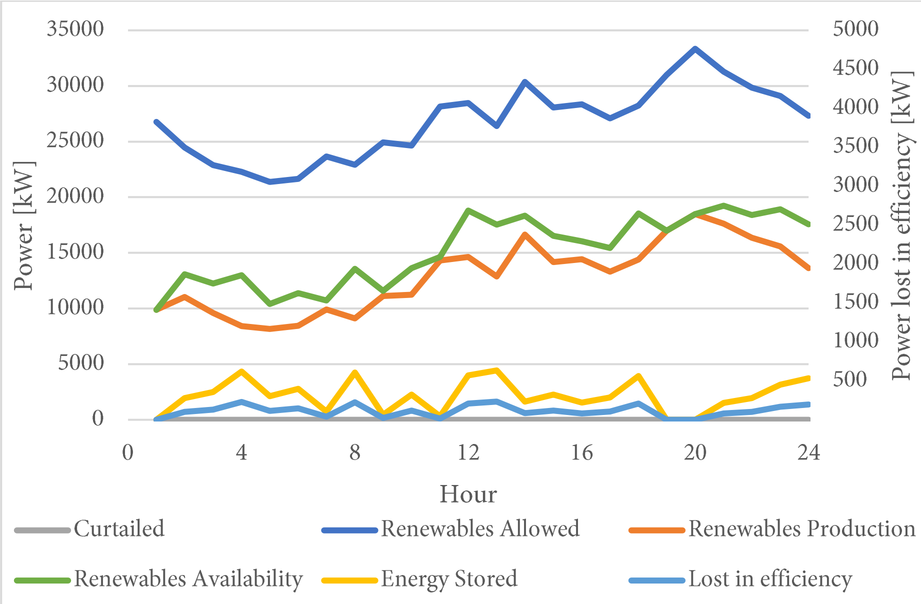


Figure 12 – Renewable balance for January 19th with VRE limit = 100%, after modifications

After these modifications, the quantity of energy to be stored is calculated at each hour after performing the economic dispatch optimization. Moreover, the Geothermal and Waste excess energy will be stored, but the constraint on the variable renewable energy allowed will only refer to wind and solar energy as it was at the beginning. In the case without limitations on renewables (VRE factor = 100%) no power is curtailed, so all the renewable energy produced is either used in the dispatch or stored; the same quantity that was previously curtailed (Figure 11 right) is now stored (Figure 12).

It is to be noted that the *Renewables* in this plot only refer to the renewables that are to be stored, thus excluding Hydro.

5.3. Comparison between HOMER and Vulcano dispatch

In this new set of simulations, the objective is to have as much as possible similar results from HOMER and Vulcano, adjusting and editing Vulcano tool and input data. Although it is acknowledged that in some cases it is not the optimal operation (e.g. the inexistence in HOMER of operational constraints leading to excessive switching on and off generators), the main goal was to test the main dispatch algorithm. The main adjustments were:

- limit on VRE penetration factor: HOMER does not limit the energy production from renewable energies, so the input value of the VRE factor allowed will be 100% in Vulcano;
- no start-up or shut-down costs: because there is no possibility to input and consider these costs in HOMER, in VULCANO these costs will be put equal to zero;
- cost of storage in HOMER: the costs of storage have been modified from default costs to the real investment and O&M costs;
- operating reserve added to Vulcano and in HOMER (20% Up and Down).

In this setup 4, simulations in different days of the year have been run:

- January 19^{th}, Sunday (high wind production, low demand);
- March 21^{st}, Friday (medium-high wind production, average demand);
- August 7^{th}, Wednesday (low wind production, average demand);
- October 26^{th}, Sunday (low wind production, low-average demand).

5.3.1. Overall Dispatch

In Figure 13 and Figure 14, the result of the economic dispatch is shown for the 19^{th} of January of the two simulations, respectively in HOMER and Vulcano. As previously stated, it has to be considered that, while in HOMER the output given is the total production from all the sources including the energy that will be stored, in Vulcano the output is only the effective production in the dispatch that will serve the load.

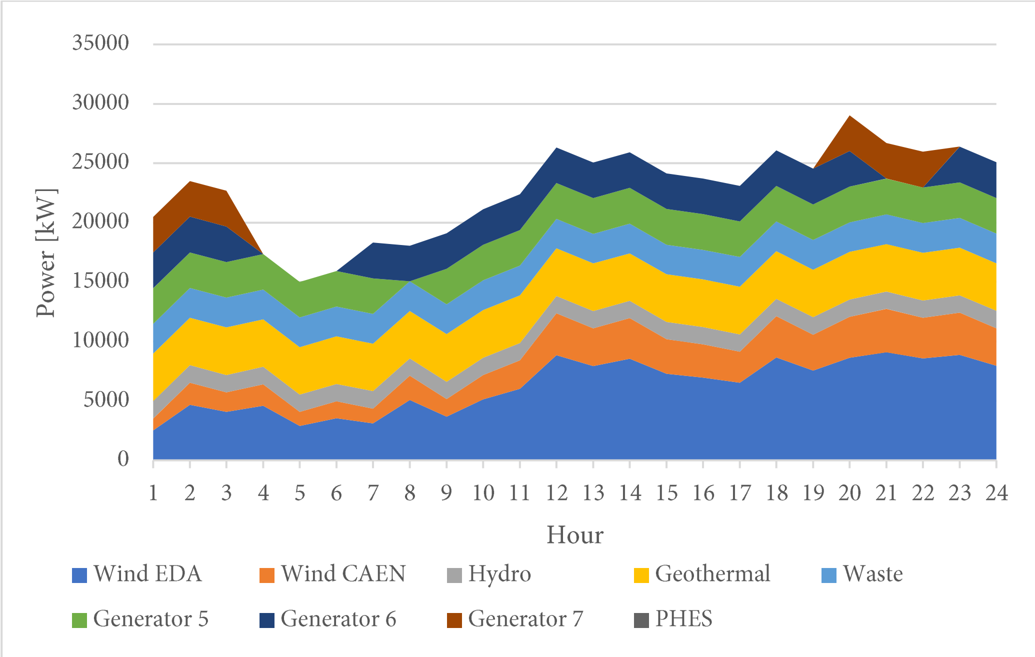


Figure 13 – Cumulative dispatch from HOMER on January 19th

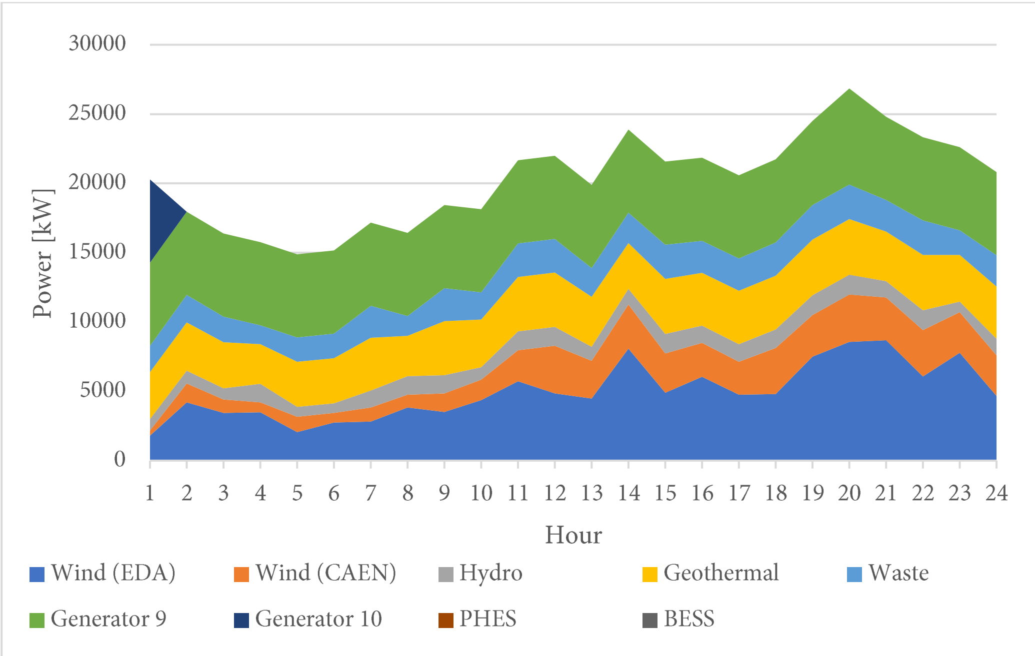


Figure 14 - Cumulative dispatch from Vulcano on January 19th

Figure 13 shows that in HOMER hydro, geothermal and RSW power plants are always working at constant power, the wind power is used as much as possible to follow the load and the peaks are covered with the commitment of new medium-sized generators. Figure 14 shows instead that the Generator 9 has both functions of baseload and load-following generators, while the other sources are adjusted: in fact, in off-peak hours the power committed from wind and hydro power plants is a smaller share, while during peak hours these sources are more exploited.

In the following sections, a more detailed comparison can be found.

5.3.2. Dispatch of thermal generators

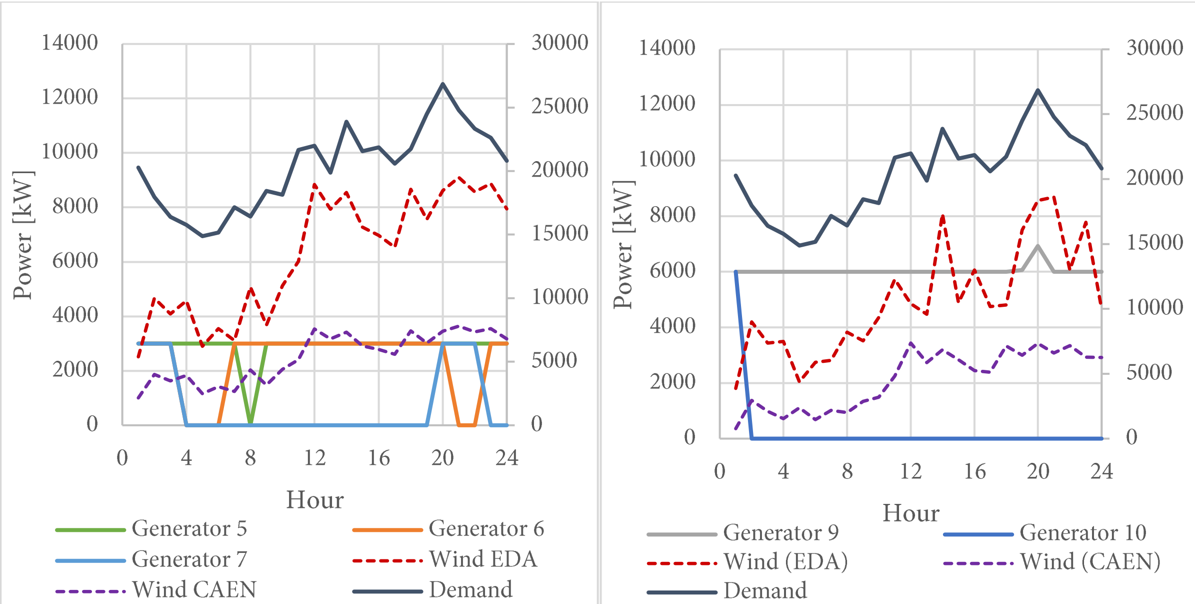


Figure 15 – Dispatch of thermal generator from HOMER (left) and Vulcano (right) on January 19th

The results of HOMER for the 19th of January, shown in Figure 15 left, have not changed consistently from the ones showed in section 5.2.2, because only small edits have been made. Still, the only relevant difference is that in this case there is one more medium-sized generator switched on only for a few hours during the peak hours (due to the increase of the operating reserve). Regarding the dispatch in Vulcano for the 19th of January, shown in Figure 15 right, one thermal generator is used at the minimum power throughout all day, while a second generator is switched on during the night peak, but then switched off.

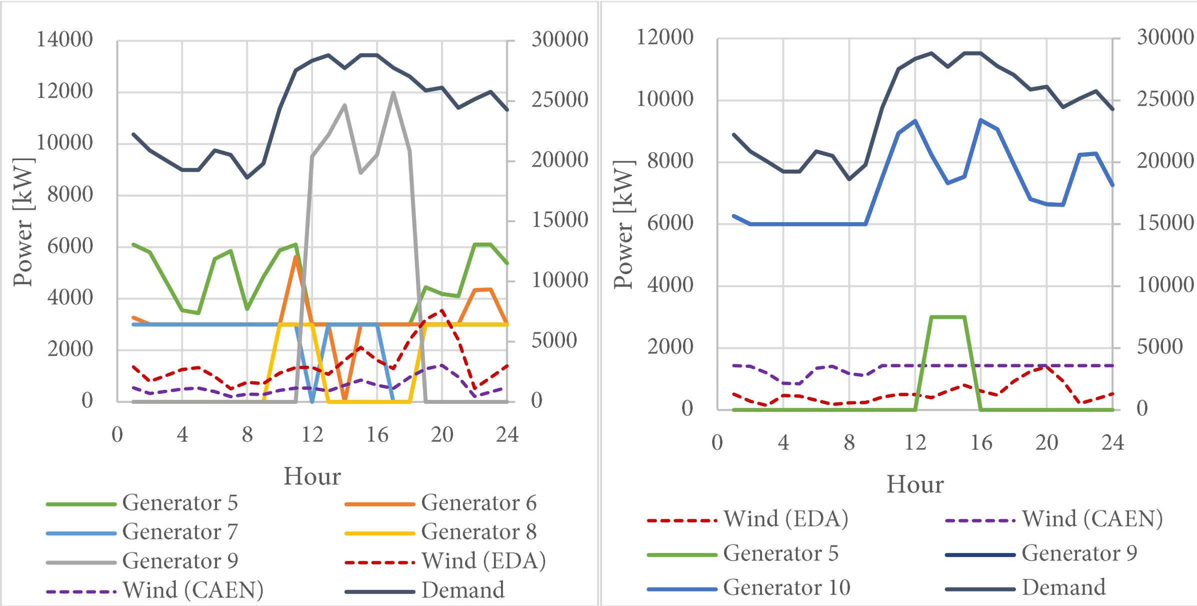


Figure 16 - Dispatch of thermal generator from HOMER (left) and Vulcano (right) on August 7th

The results for the 7th of August, a day with a high demand and low renewable availability (Figure 16), present a very different scenario: in HOMER, four medium-sized and one big-sized generators are used, with the Generator 9 turned on only during afternoon peak hours; in Vulcano, two big-sized generators work during all day at minimum power in the night and following the load during the day with an additional medium-sized generator switched on in hours of low wind production and high demand.

The preference of Vulcano tool for big-sized generators would have been justified in the simulations saw in 5.2.2, where this behaviour could have been attributed to the start-up and shut-down costs that would make difficult turning off the generators, but because in this case, these costs are zero there would be no reason for the big-sized generators be preferred over the medium-sized ones. Further, in the simulation of January 19th, an average of 16% of the energy produced from Wind, Geothermal and Waste Power Plants is not committed in the dispatch (Figure 14). From the results, we can see that this energy is stored, but, from the optimization point of view, we cannot consider that is stored, because the charging operation happens after the dispatch meaning that in principle the renewable energies would be curtailed in order to keep the Generator 9 switched on. For the simulation of August 7^{th}, it can be noticed in Figure 16 right that the wind production also decreases during morning hours, but because the overall wind energy produced is low, the effects of this behaviour are less significant.

Consequently, simulations were run specifically to check this behaviour:

- on a first attempt decreasing the demand to an amount that would have made one medium generator along with the renewable generators sufficient to satisfy it; the result was that renewables were partially stored and partially curtailed while the big-sized generator was still used at the minimum power. This simulation was done to prove that even in a case where there was no need for big-sized generators because one medium-sized one would have been enough to satisfy the demand, the first type was still preferred.
- in a second stage, a simulation without the two big generators was made; in this case, not only the medium-sized generators were used in a similar way to HOMER, but also the overall cost for the energy production decreased with respect to the previous case as shown in Table 8. With these simulations, it is possible to compare the results from Vulcano and HOMER.

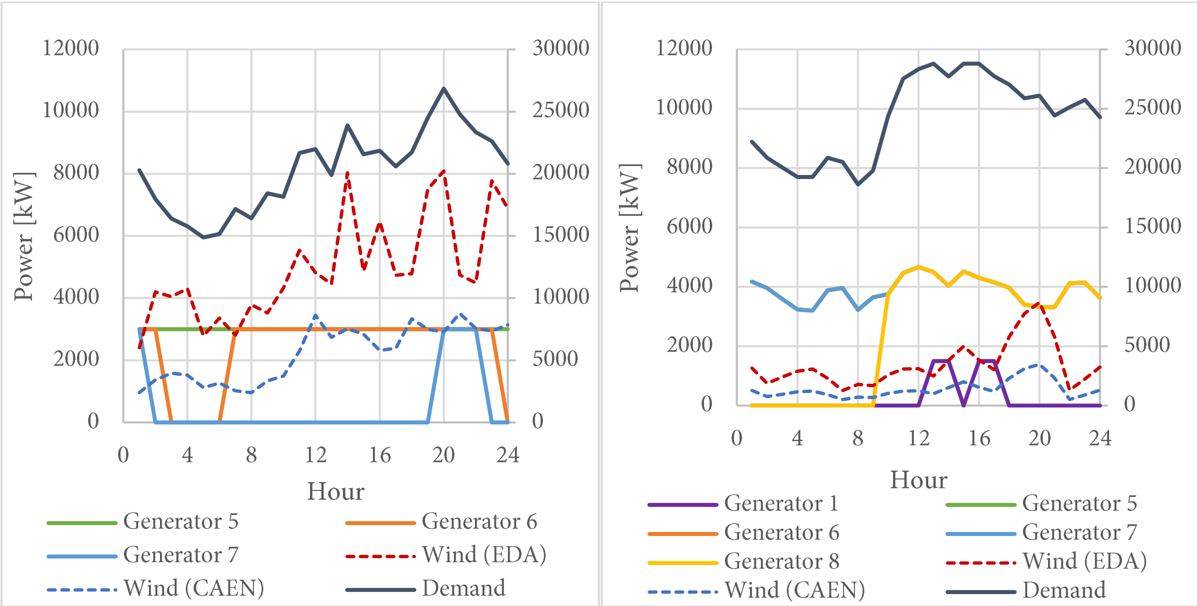


Figure 17 – Dispatch of thermal generators from Vulcano without big-sized generators for January 19th (left) and August 7th (right)

For January 19th results from Vulcano shown in Figure 17 right can be compared with the results from HOMER in Figure 16 left. Comparing the unit commitment of thermal generators in both cases generator 5, 6 and 7 are used, always at the minimum power; in HOMER, Generator 5 is always on except for one hour, while Generator 6 is turned off two times in the early morning and in the late evening, and Generator 7 is turned on two times during the peaks at hours 1 and 20. In Vulcano, Generator 5 is always on, Generator 6 is switched off in the early morning and at the end of the day, and Generator 7 is also switched on at the first hour and in correspondence of the evening peak. As shown by the data of Table 7 the error of energy production is decreased with respect to the previous simulations.

Table 7 – Dispatch numerical results

		Fuel Oil			Wind		Hydro	Geothermal	Waste
		Gen. 5	Gen. 6	Gen. 7	EDA	CAEN			
Vulcano	Energy production	72000	57000	12000	118722	53553	29328	90127	53847
	Working hours	24	19	4	24	24	24	24	24
HOMER	Energy production	69000	57000	18000	150744	60298	35062	96000	60000
	Working hours	23	19	6	24	24	24	24	24
Error [%]	Energy production	4.3	0.0	33.3	21.2	11.2	16.4	6.1	10.3
	Working hours	4.3	0.0	33.3	0.0	0.0	0.0	0.0	0.0

In the case of the 7th of August (Figure 17 right) both the big-sized generators are needed and a medium one is turned on during an afternoon peak; if the two big generators are erased, the system will need 4 medium-sized generators and one small generator.

On the economical point of view, the simulation without big-sized generators is less expensive in both days simulated (Table 8), because it allows a higher penetration of renewables, which have zero costs. On the other hand, from the grid management point of view, generally, the first situation is preferred, especially in the case where a fifth, small-sized generator would be turned on because big-sized generators are much more reliable and have bigger inertia. In this type of simulation, in fact, demand and renewable availability data have been considered as already known with complete certainty, but in real operations, the grid manager has to face sudden changes which are easier to meet with these type of generators.

Therefore, while Vulcano replicates real behaviours, with the perspective of having a tool flexible and able to simulate high renewable shares systems, this behaviour of the dispatch algorithm is undesired, not only because the curtailment of renewable energy production is to be avoided (as it will be proved in the next paragraph, Figure 20), but also because the overall cost would increase as shown in Table 8.

Table 8 – Overall daily cost of the system

Overall daily cost of the system		
	January 19th	August 7th
Vulcano - with big-sized generators	23464.7 €	51594.1 €
Vulcano - without big-sized generators	18377.7 €	44644.6 €
HOMER	19157.3 €	46174.9 €

From the analysis of these two cases, the problem of overuse of big-sized thermal generators was identified and will be further addressed in subsection 5.3.5.

5.3.3. Dispatch and Shares of Renewables

One of the objectives of a good dispatch is to always exploit energy produced from renewable sources. This always happens in HOMER, while for Vulcano is strongly dependent on the type of system because of the generators constraints. With respect to the simulation in subsection 5.2.2, a much higher percentage of renewables is found in the final dispatch, having increased the limit of VRE penetration factor to 100%. The following Vulcano results shown are obtained from simulations without big-sized generators, being comparable with the results obtained from HOMER as noticed in the previous paragraph.

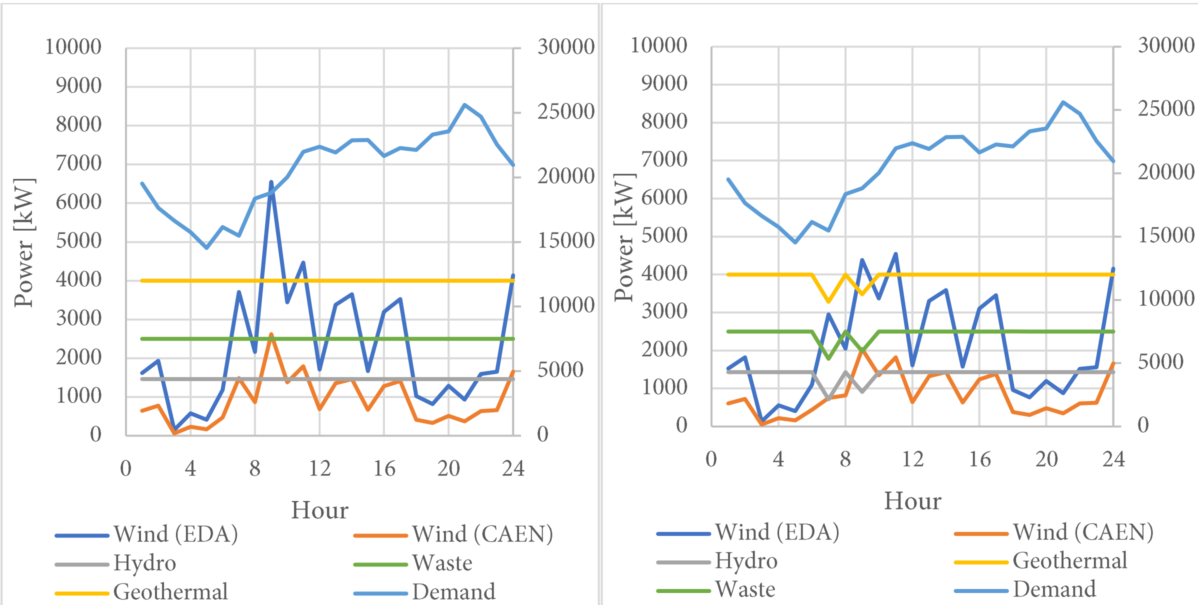


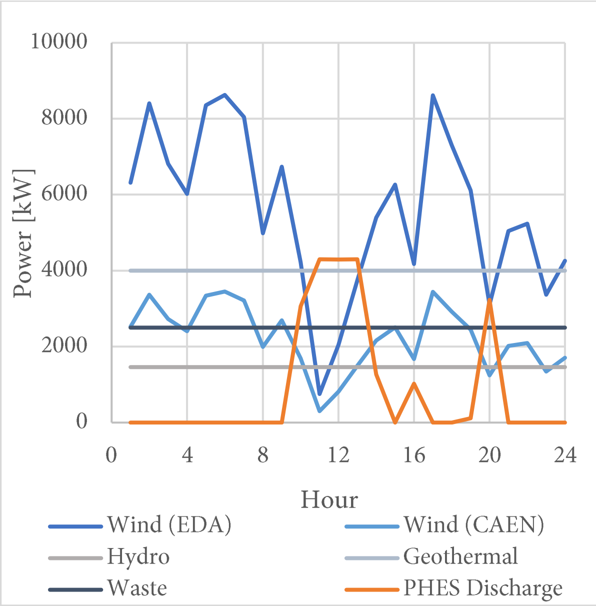
Figure 18 – Renewables Dispatch from HOMER (left) and Vulcano (right) on October 26th

As shown in the results for the 26th of October in Figure 18, the main difference between HOMER and Vulcano is that the first allows more renewables in the dispatch, in fact, even if there is no limit on the renewables in Vulcano the renewables are limited by the thermal generators constraints. Nevertheless, the difference between the renewable penetration factors is only 2%, as shown in Table 9.

Table 9 – Average daily renewable penetration

Average daily renewable penetration		
	Not including Geothermal and Waste	Including Geothermal and Waste
October 26th		
Vulcano	21.21 %	53.11 %
HOMER	23.04 %	55.56 %
March 21st		
Vulcano	37.42 %	66.13 %
HOMER	45.56 %	76.17 %

In the simulation of the 21st of March, it can be noticed in Figure 19 that at hour 11 there is a sudden drop in the wind production, which is filled by the energy stored during the previous hours in both simulations. Another difference is the same found in the simulation for the 26th of October, which is that wind power committed in the dispatch is higher in HOMER than in Vulcano, but in this case, the gap is much higher as described by the average daily renewable penetration percentages in Table 9.



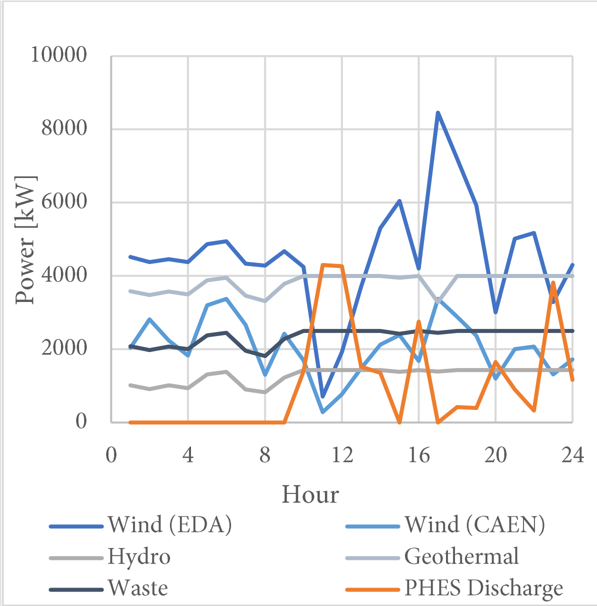


Figure 19 - Renewables and Storage dispatch from HOMER (left) and Vulcano (right) on March 21st

The preference of Vulcano for big-sized generators has also an effect on renewable energy production. In Figure 20 the renewable balance plot of Vulcano for the 21st of March is shown to prove that in some cases this behaviour leads to the curtailment of renewable energy. This happens because when the big-sized generators are forced in the on-state the renewable excess could be too high up to the point where the charge power exceeds the maximum charge rates or where the storages are full and renewable energy has to be curtailed: in fact, at hour 5 and between hour 17 and 19 the BESS storage is full and the charge power exceeds the maximum charge rate of the PHES; at hour 24 both the storage systems are full. This case has to be avoided. In the simulation without big-sized generators, no renewables are curtailed (Figure 20 right).

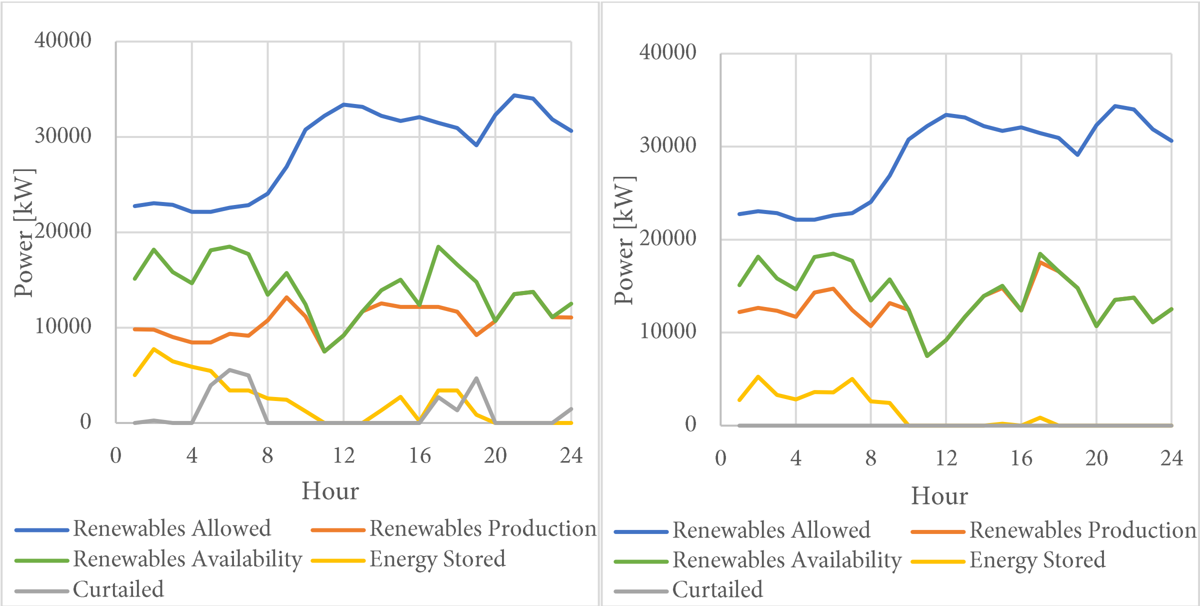


Figure 20 – Renewable balance plot with big-sized generators (left) and without (right)

5.3.4. Storage Dispatch and State of Charge

For the reasons explained in subsection 5.3.2, to compare the results of HOMER and Vulcano, the simulations are done excluding the big-sized generators from the data set. Only the most relevant results are shown in Figure 21 and Figure 22 corresponding respectively to the 19th of January and the 21st of March. The results of the 7th of August and of the 26th of October are not particularly relevant, being two days with low wind production, hence with a reduced use of storage systems.

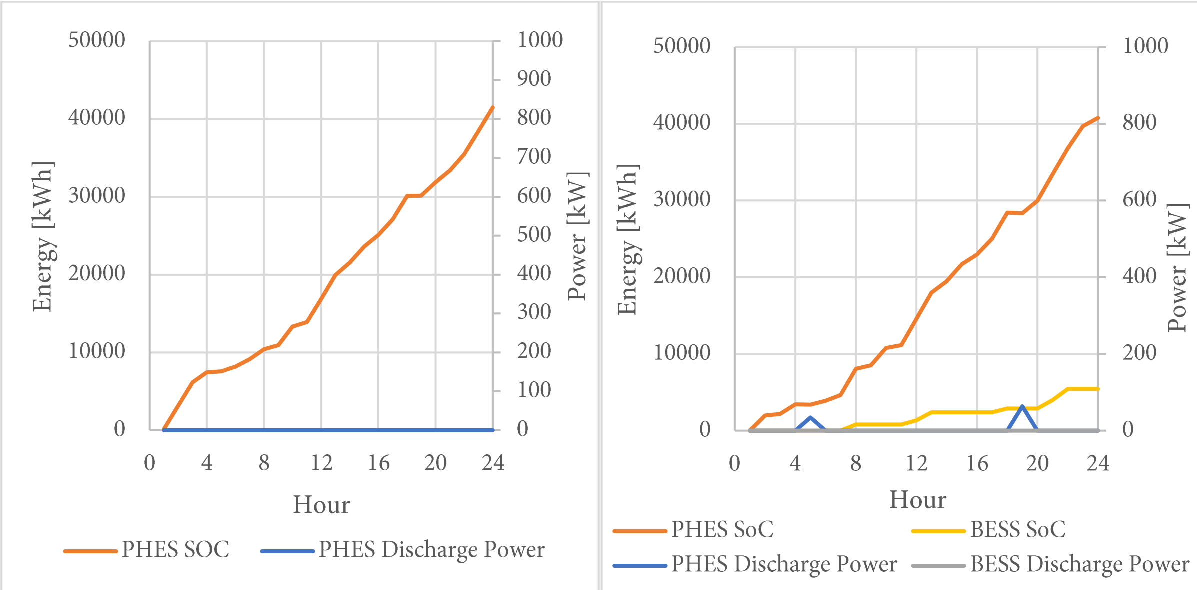


Figure 21 – ESS Dispatch and SoC from HOMER (left) and Vulcano (right) on January 19th

The Pumped Hydro Storage SoC of January 19th has the same trend for HOMER and Vulcano, as can be noticed from the small values of error in Table 10 and from Figure 21. But while in HOMER PHES is only charged and never used in the dispatch (Figure 21 left), in Vulcano is used two times, even if for small values of power (Figure 21 right), which is the opposite situation of the results in subsection 5.2.2. In Vulcano, the BESS is also charged up to less than half of its capacity (Table 10).

Table 10 – Storage simulation results for January 19th

		Vulcano	***Homer***	***Error [%]***
PHES	Energy stored [kWh]	40882.9	49581.5	17.5
	Energy dispatched [kWh]	97.6	0	100
	Average SoC [%]	41.3	46.2	10.6
	Peak of energy content [kWh]	40780.2	41482.8	1.7
BESS	Energy stored [kWh]	5439.7	0	100
	Energy dispatched [kWh]	0.0	0	0
	Average SoC [%]	14.0	0	100
	Peak of energy content [kWh]	5439.7	0	100

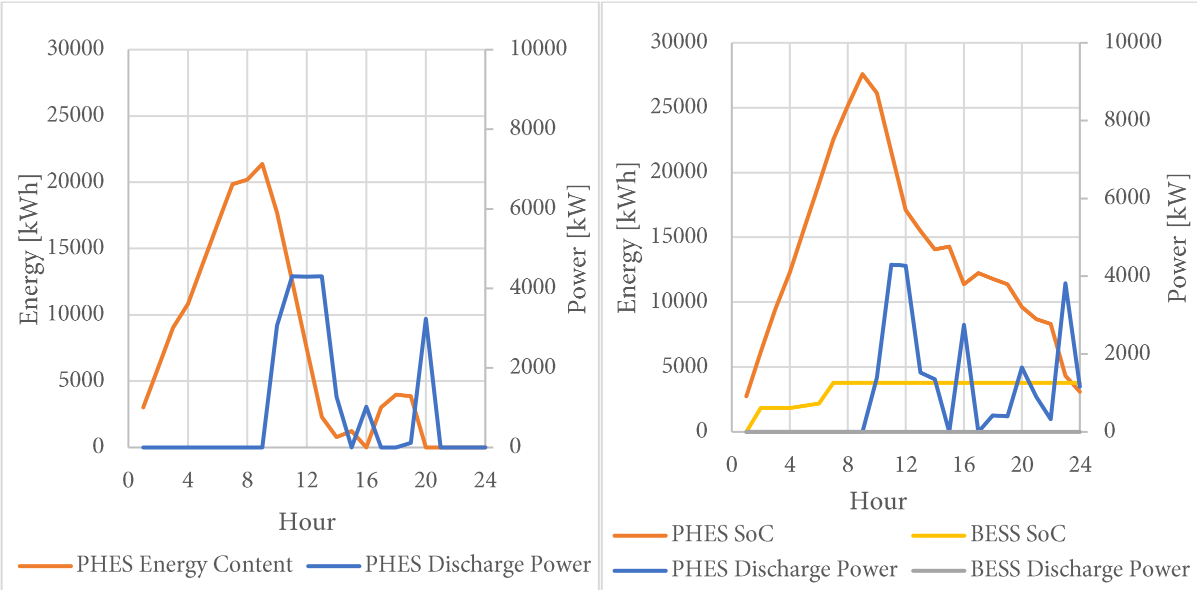


Figure 22 - ESS Dispatch and SoC from HOMER (left) and Vulcano (right) on March 21st

For the day of March 21st, the behaviour of the PHES is similar in the two software tools (Figure 22): the storage is, in fact, charged almost constantly during the first hours of the day until hour 9 when the behaviour becomes different. In HOMER, where the energy content reached the peak of 21379 kWh, the storage is completely discharged until 16; in the afternoon is shortly charged and then again completely discharged. In Vulcano, where the peak was of 27590 kWh, the storage is discharged less rapidly until the end of the day, when is still not completely discharged. Moreover, in Vulcano, the BESS is charged, even if for a small amount of energy, while not being used at all in HOMER. Overall, as shown in Table 11, the behaviour of the PHES is similar considering the energy stored and dispatched. The maximum value of energy content reached is also similar, while the average SoC during the day is very different, reaching a value of the error equal to 89.5%, meaning that if the general behaviour is similar, in Vulcano the PHES remains charged for more hours than in HOMER. Regarding the BESS, as also noted in the figure, the only behaviour common to the two tools is that it is not used in the dispatch.

Table 11 - Storage simulation results for March 21st

		Vulcano	***Homer***	***Error [%]***
	Energy stored [kWh]	28669.0	30852.0	7.1
PHES	Energy dispatched [kWh]	24296.6	21596.4	12.5
	Peak of energy content [kWh]	27590.1	21378.6	29.1

	Average SoC [%]	32.7	17.3	89.5
BESS	Energy stored [kWh]	3788.1	0	100
	Energy dispatched [kWh]	0	0	0
	Peak of energy content [kWh]	3788.1	0	100
	Average SoC [%]	24.0	0	100

The different behaviour between HOMER and Vulcano can only partially be attributed to the fact that in Vulcano excess geothermal and waste power is stored, because in this simulation these plants work at their nominal power 22 hours over 24, therefore only a small quantity of the energy stored is coming from these plants. As observed in subsection 5.2.2 the difference resides in the dispatch algorithm, that in HOMER allows higher renewable

5.3.5. Issues in Vulcano code

Overuse of big-sized generators

The reason why Vulcano always prefers big-size generators is because the code uses the priority list method for the choice of the generators. The priority listing is a function executed before the loops in which optimization is performed; it creates a list of the generators prioritized by their cost; this order will remain fixed for all the hours irrespective of the demand and will determine the order in which the generators (including renewables and storage) will be switched on, meaning that there will not be a scenario where the more expensive generators will be switched on without having already the ones before them in list in on state. The cost considered to make the priority list is the average cost at full power:

$$Full\ Average\ Cost = (Noload\ cost + P_{max} * Incremental\ HR) * \frac{Fuel\ cost}{P_{max}} \qquad (5.1)$$

In the simulation of Figure 15 left, the fuel cost of big-sized generators is the same as the one of the medium-sized while the no-load costs are ten times higher than the ones of the medium generators. This would explain why once turned on, the big-sized generators are difficult to turn off not in the case without any start-up or shut-down costs. But even if the no-load costs are put equal to the ones of the medium-sized generators the big ones will still be preferred.

This happens because in the calculation of the full average cost the parameter of maximum power is at the nominator and has a strong influence on the resulting value. Therefore, the big-sized generators result as the cheapest ones preferred and switched on before the medium or small-sized generators.

This way of calculating the cost, though, does not consider that the generators could be used at a power much smaller than the maximum one (in the case of Figure 15 right, in fact, thermal generators work always at the minimum power).

This choice was originally made because the code was written on the basis of Corvo and Terceira islands' energy systems, which had a very low (in the case of Corvo almost zero) renewables penetration factor; in addition, the electricity grid manager, EDA (Electricidade dos Açores), preferred to use the big-sized generators always switched on. The goal of the analysis now has changed: along with analysing the real system, the tool has to give the possibility to analyse also a possible future scenario with more renewable production and with storage. Moreover, the overall cost of the system would decrease.

Hence, to solve the problem, the listing order had to be more sensitive to the load at which the generators are effectively dispatched. Thus, in order to change the listing order, the power used at the denominator was modified to reflect a percentage of the nominal power, equal to the average load factor of thermal generators, which was chosen to be 80%.

No cost for renewable generators

If the energy that satisfies the demand is all produced by renewable energy source, the program will be unable to work, since the dispatch optimization is based on equivalent fuel cost, which for the renewables is zero. This situation was verified in the simulation for the 21st of March. This problem has its roots in the initial development of the code, since the initial purpose was, in fact, to simulate a real system, where a situation in which all the renewables could completely satisfy the demand was not considered.

To temporarily solve this problem, a simulation can be done adding an equivalent fuel cost for the renewables, for example using the levelized cost of electricity for renewable technology. Thus, this change will only affect the overall cost results, albeit keeping the unit commitment optimization untouched.

6 Improving Vulcano model

As previously reported, there was a set of need improvements to be made to the code, that will be further developed in this section. Nonetheless, the fact that many modifications and approximations had to be made in Vulcano indicates that this tool is more able to reproduce some mechanisms and constraints that happen in real operations, with respect to HOMER which is not so much sensitive to some operational constraints that the grid manager has to consider [14].

6.1. Priority listing method

For the analysis of islands' energy systems, it is useful to have a tool that can simulate both the behaviour of energy systems with low renewable energy penetration (less than 30%), like the ones of the Azores, and at the same time simulate the behaviour of a system with increasing energy production from renewable energy sources and with the addition of storage energy systems. Consequently, to solve the problem of the priority listing method, described in section 5.3.5, a new specification was added in the initial GUI where the user will have to decide if the energy system to simulate is a "Low Renewable Penetration System" or a "High Renewable Penetration System". This specification will allow the code to adapt the calculation of the priority list, as follows:

- Low Renewable Penetration System: the priority list calculation is kept the same (Equation (5.1)), since as seen it is the most suitable for energy systems with a baseload assured by thermal generators;
- High Renewable Penetration System: in Equation (5.1), P_{max} is considered to be 80% of the rated power, since it is assumed that in energy systems with high penetration of renewables thermal generators will work as renewables backup and so, below the nominal power.

As a rule of thumb, the renewable penetration of a system can be considered low when this factor is smaller than 30%.

Regarding the second problem addressed in section 5.3.5, since the installed renewable power is not sufficient to provide enough energy to satisfy all the demand, the case verified for the simulation of the 21st of March was an isolated case, not justifying a major modification of the optimization algorithm. However, if this tool aims to be reliable enough to simulate high renewable penetration systems, the code will have to be modified in order to work even when there are no thermal generators, otherwise, the equivalent cost will have to be mandatory.

6.2. Renewable resource input data

Until now, renewable resource was directly inputted as renewable power (after technology efficiencies), not existing the possibility to input renewable resource data, like wind speed, solar radiation, etc., that are normally measured on-site when there is the intention to deploy a certain renewable technology on an existing energy system. Thus, one of the improvements made was the possibility to input the wind speed, for the model to convert it in wind power. This was a function already accounted for, but not yet implemented. Consequently, a generic wind turbine power curve has been used for the calculation of wind power, being further explained in the user’s manual produced how to change the power curve if needed.

The possibility to input the Solar Radiation instead of Solar Power was considered, although not implemented. In this case, it was chosen not to implement it since the calculation of the solar power, starting from the Global Horizontal Solar Irradiation, depends on the solar angles, hence the user would need to input also the location of the system and the days of the year in which the system is simulated. This would increase the complexity of the tool, making it difficult to comply with the central goal of being able to simulate a set of different time horizons and systems without needing too many system input details. Nevertheless, nowadays there are many web applications that allow to calculate the hourly power output in few minutes or seconds, receiving as input the location and details of the system (orientation, solar angle, type of PV panel), which [46], [47], [48], [49] are examples.

6.3. Multi-day simulations

In Vulcano, the Multi-day simulation mode allows to input data (demand and renewable availability) in an excel file of customized length, while on the GUI the only input needed is the number of months, days, hours that the user wants to analyse.

6.3.1. Simulations results

Until now the simulations were made with a time horizon of one day. Although these simulations are useful to understand how generators are committed, they only offer a partial view of the results, not giving insights of how the intraday transitions are made, which is particularly important when studying energy storage systems. In fact, to analyse the storage integration in the system a time span of some days or a week is needed, to consider not only his function of peak shaving but also the function of increasing renewable penetration.

Terceira energy system is simulated again in both software to validate Vulcano tool operations also in Multi-Day mode. In this case, differently from the "Typical Day" simulations done in section 5.3, the improved version of the code is used with the "High Renewable System" mode and start-up and shut-down costs are restored. Four different months were simulated, one for each season, corresponding to those of the days simulated in section 5.3: January, March, August and October. Nevertheless, only January results are considered relevant to report in terms of storage operation, since January has the highest wind production, hence storage potential.

To better analyse the dispatch of thermal generators only three days are considered in Figure 23 and Figure 24.

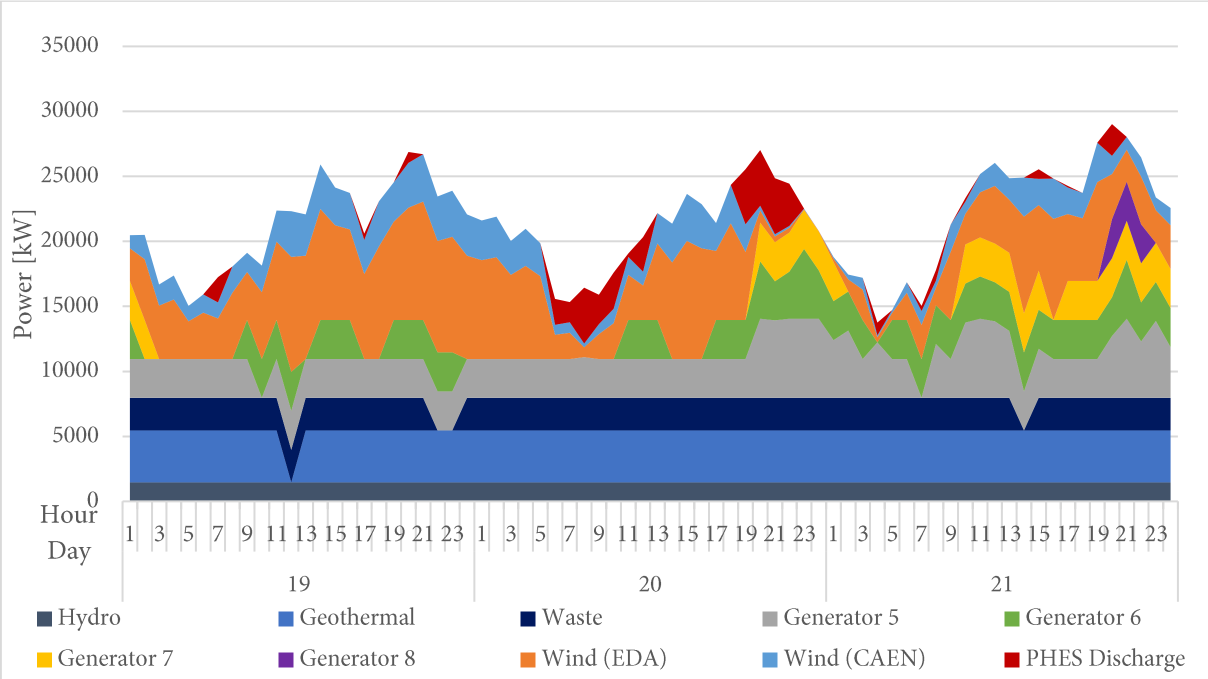


Figure 23 – Cumulative dispatch from HOMER during the days 19th – 21st of January

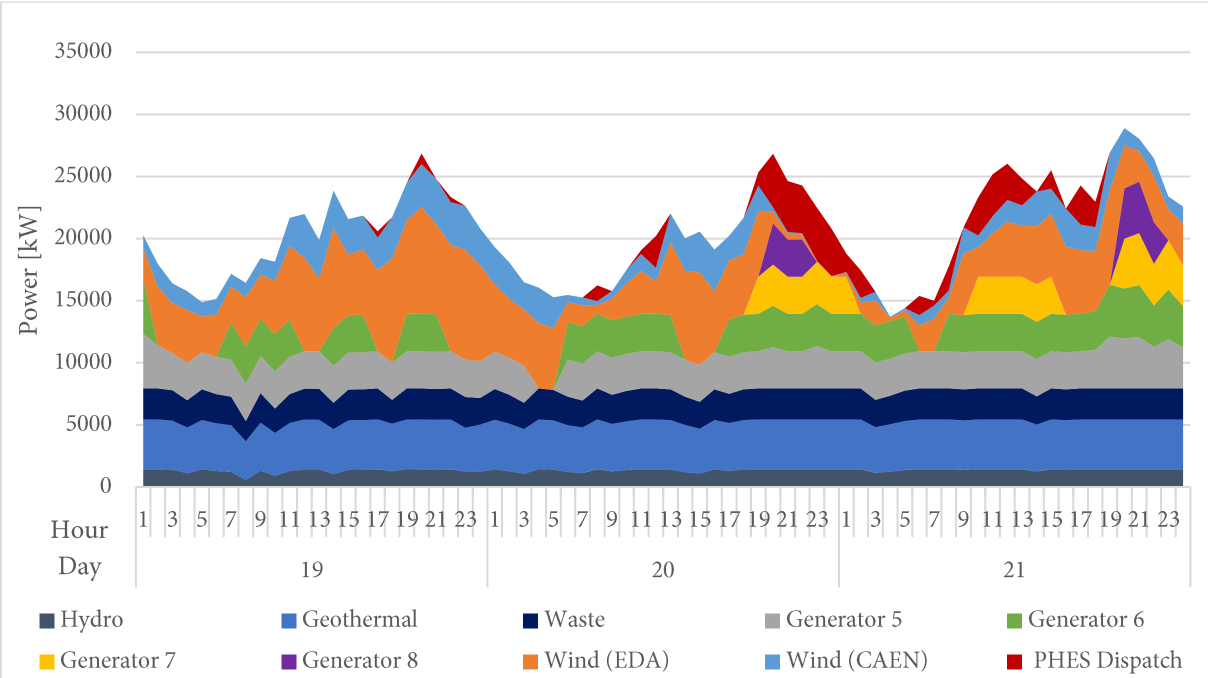


Figure 24 - Cumulative dispatch from Vulcano during the days 19th – 21st of January

The results of HOMER (Figure 23) and Vulcano (Figure 24) have a very similar behaviour during most of the hours; along with differences already highlighted in previous simulations, the differences that can be noted is in how some peaks and off-peaks are handled. For example, during hours 6-10 of day 20th HOMER keeps on only one generator and uses the energy stored, while Vulcano switches on a new medium-sized generator. Moreover, during the evening peak (hours 18-21) of the same day, HOMER satisfies the increase in demand with an increase in the power of the three generators already in on-state, while Vulcano prefers to switch on a new generator. This is particularly unexpected because in these Multi-Day Simulations the start-up and shut-down costs in Vulcano have been restored.

This behaviour could be attributed to an unexpected operation of Vulcano: it can be noted how the thermal generators of the same size, when committed, always assume the same power; this means that with three working generators if one of the generators has to increase its power, the same should happen to the other two. Since this problem was only noticed in the final analysis of the system, it was not treated in this project. However, it can be the object of future research and improvement of the code.

In the following figures, the dispatch of wind and storage in the transition from the third to the fourth week of January is shown. An interval of one week is displayed from Wednesday, the 16th to Tuesday, the 22nd to analyse how the storage is charged and discharged over a weekend.

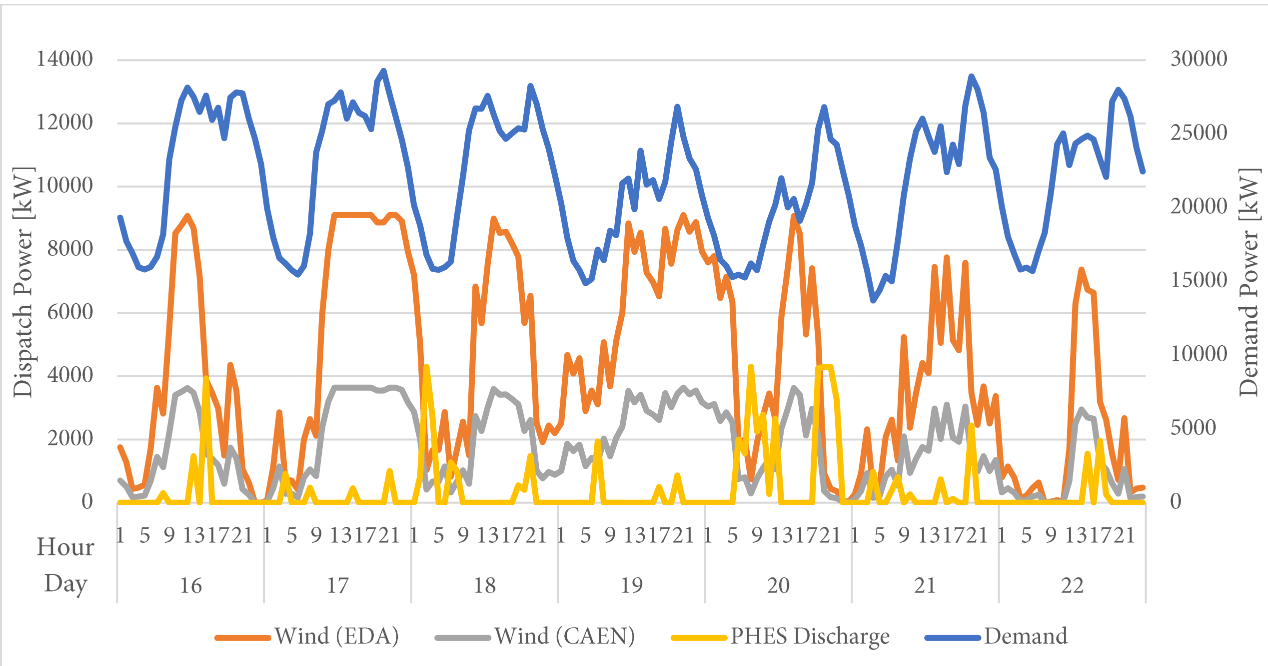


Figure 25 – Renewables and storage dispatch from HOMER – January 16th to 22nd

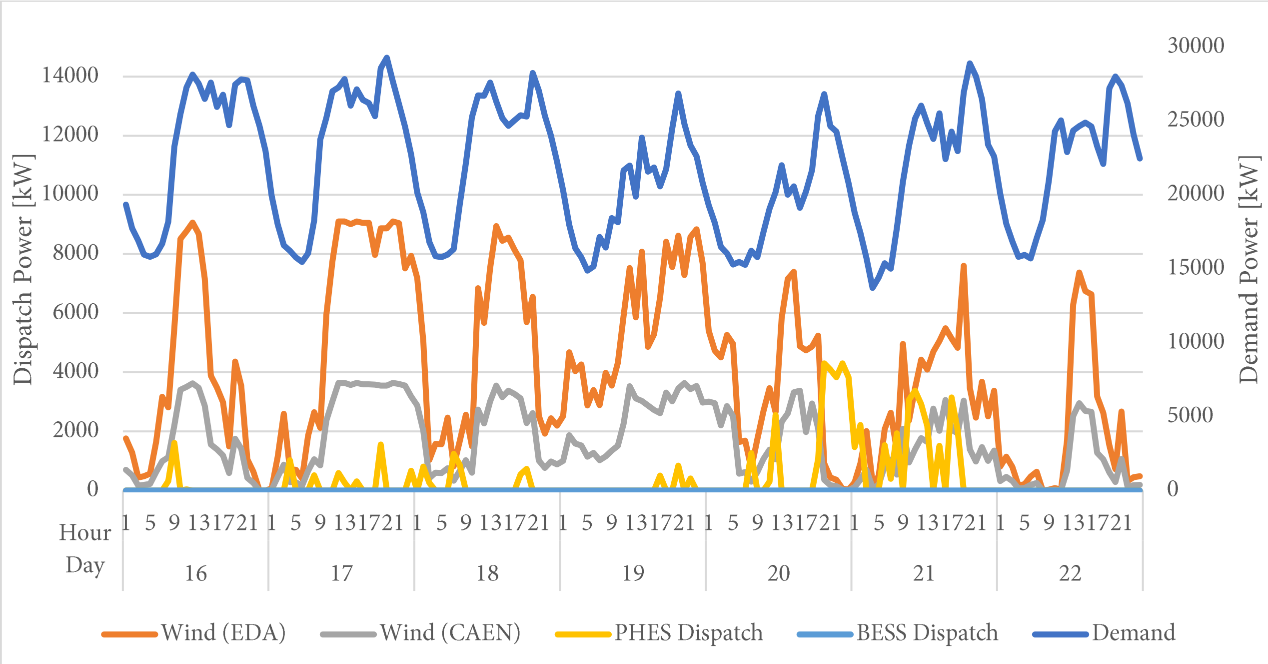


Figure 26 - Renewables and storage dispatch from Vulcano – January 16th to 22nd

The behaviour of the storage is very similar in HOMER and Vulcano; in Figure 25, Figure 26 and Figure 27 can be noted how, in both cases, a great amount of energy is stored in three days of high wind production (17,18,19) and part of it is used during the peak at hour 20 of the 20th. Instead, it can be noted how in the next days the energy stored is used in the dispatch also during off-peak hours. In general, the pumped hydro storage does not remain charged for a long time but is discharged in a few hours, as it can be noticed by the peaks in the curve of the SoC (Figure 27). In Vulcano, this can be attributed to the fact that the storage is treated as a generator, and because it does not have a high cost, as soon as some energy in the storage is available it will be used, prior to the one from the generators. In fact, in Vulcano, where also Geothermal and Waste energy is stored, the BESS is charged alongside the PHES, although it is never used in the dispatch, having an equivalent fuel cost which is twice the one of PHES.

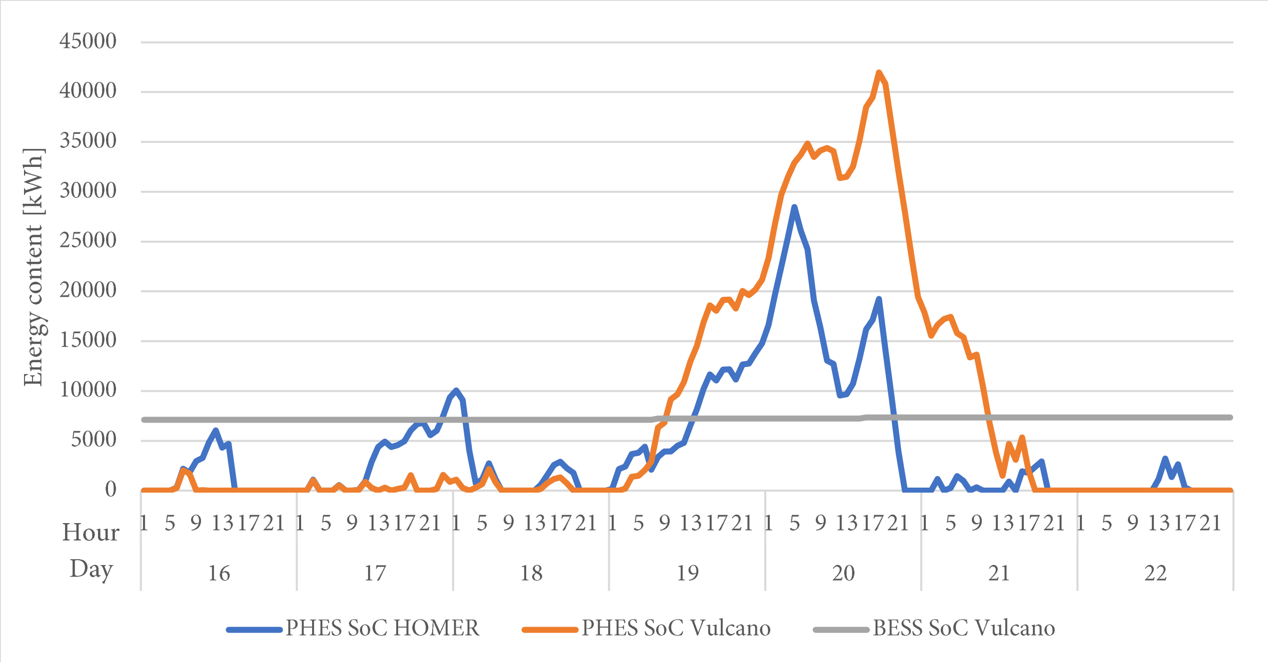


Figure 27 – Comparison of HOMER and Vulcano SoC evolution – January 16th to 22nd

Considering all the data from January the same behaviour happens for the transition from week 4 to week 5, while during other weeks the storage is always charged and discharged within the same day.

As anticipated, the other months do not show relevant phenomena in the Multi-Day mode with respect to the analysis of a single day, and for this reason, their results are only reported in the annexes.

6.4. Improving Storage Operations

Although the HOMER and Vulcano results showed the same behaviour, the fact that the discharge of the storage is performed without looking to the cost-opportunity of renewable availability, neither to the stored energy availability in the dispatch time horizon, makes its behaviour irrational and far from real operations. Accordingly, two first steps were done to improve storage operations:

- Input of minimum and maximum SoC of storage systems: this was a feature that was already considered in the first model of storage integration in the tool, but that was not implemented in the code. The minimum and maximum SoC are received as input in the GUI, imposing that the initial SoC of the storage has to be equal or higher than the minimum SoC;
- Possibility to choose between inputting a maximum percentage of renewables allowed (VRE penetration factor) or a minimum thermal share of the total energy production. This feature was inserted to improve the storage operations particularly in systems like the ones of the Azores, where a minimum baseload can be provided by the thermal generators. This will consequently avoid that the storage will be discharged in off-peak hours, during which the thermal generators will ensure the power production. This is also an alternative criteria of dispatch, which could be particularly useful in cases where the grid manager itself needs to operate with this constraint for grid stabilization reasons.

These first two actions, though, were not sufficient to effectively improve the storage behaviour. As shown by the results of the Multi-Day simulations, the PHES is always discharged when available, while the BESS is charged and hardly ever discharged. At first, the two types of storage were sized for the opposite function: the battery (which has a higher charge/discharge rate) was supposed to store energy for short periods of time, to cover the daily peaks, while the pumped hydro was sized to store energy for longer periods of time, with a time horizon of three days [13]. Indeed, having the storage outside the dispatch optimization loop, and considering them in the priority list of generators, from which energy can be withdrawn when available and necessary, leads to pumped hydro to be discharged always in few hours, since it has a lower cost than all the small and large generators, while batteries are never discharged due to their higher cost, above all generators. Thus, a major flaw of the storage behaviour is the fact that PHES is always charged before BESS because the charging operation is outside the optimization process, as explained in section 3.2.4 and as graphically shown in Figure 28.

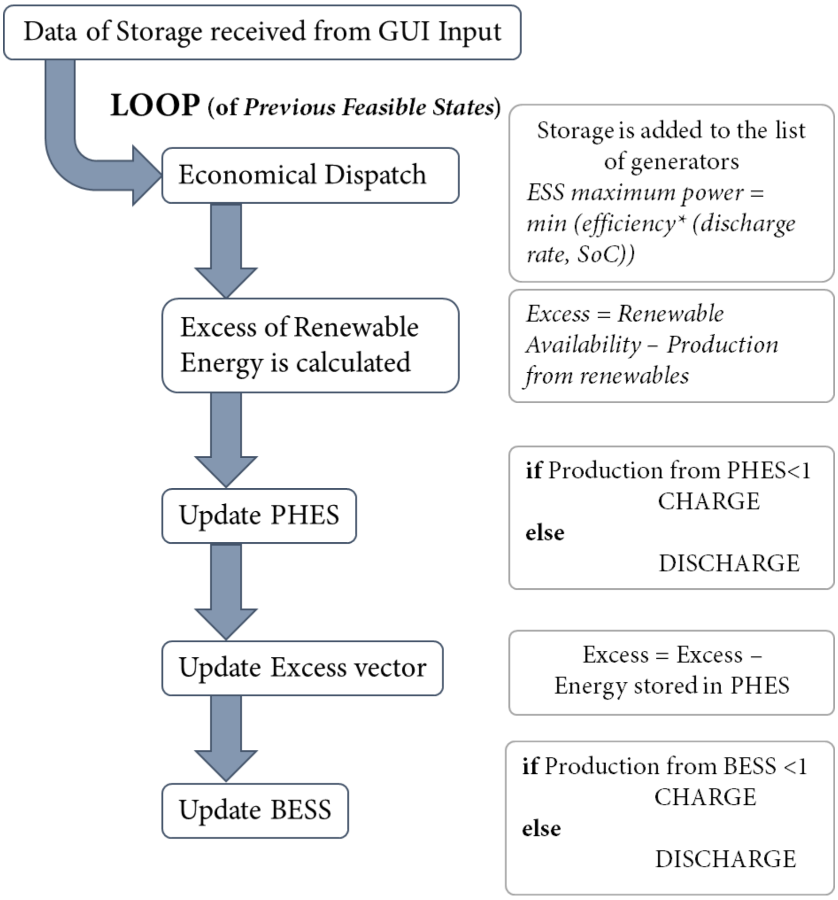


Figure 28 – Scheme of storage operations

As can be observed in Figure 28, the energy sent to the storage is the result of an energy balance between what is produced (output of the dispatch algorithm) and what is available. In fact, the algorithm treats all energy sources as generic generators, committing the necessary energy only considering the costs and the different operational constraints. Yet, this behaviour needs to be improved not only because it will not give the optimal solution for the storage operations considering a certain time-horizon, but also because it implicates some problems and unclarities in the code.

One problem raised regards the costs of the system. If, for example, the geothermal generator will not be in the dispatch for one hour, even though we are considering its production for the storage during that hour, from the optimization point of view that generator will be turned off, hence shut-down costs will be considered, while fuel costs for the operation will not be considered. In the cases considered in this project, this is not a real problem because this type of generator, considered as a renewable source of energy, does not have these costs, moreover, the current analysis is not focusing on the system costs, but on the unit commitment operation; however, it is a problem that should be considered for a real improvement and generalization of the tool.

Another implication is on the type of data that can be obtained as output: in fact, it becomes difficult to understand all the different contributions from the different energy sources to the energy stored. This is something that becomes particularly interesting when some power has to be curtailed since the decision to curtail one generator/power plant made by the grid manager usually follows some logic dependent on the local energy prices and grid constraints, therefore it is a problem that with increasing renewable penetration will have to be analysed in more depth.

To investigate the problem, a literature research has been carried out, and it was found that the majority of the models where the priority list method is used are studies of large energy systems with a predominance of thermal generators ([50], [51], [52], [53]). Therefore, other models and possible solutions have also been studied as described in the literature review (section 2.2), which possible solutions are presented in the next subsections.

6.4.1. Adopted solutions

A first attempt to improve the behaviour of storage was to find some constraints that could influence the decision of charge and discharge operations, albeit not being included in the dispatch problem.

Conditions for charge and discharge operations

The first condition tested was the imposition of a minimum power of charge and discharge for the PHES; this condition aimed at avoiding that the turbine worked in the low-efficiency zone [54] (Figure 29 left).

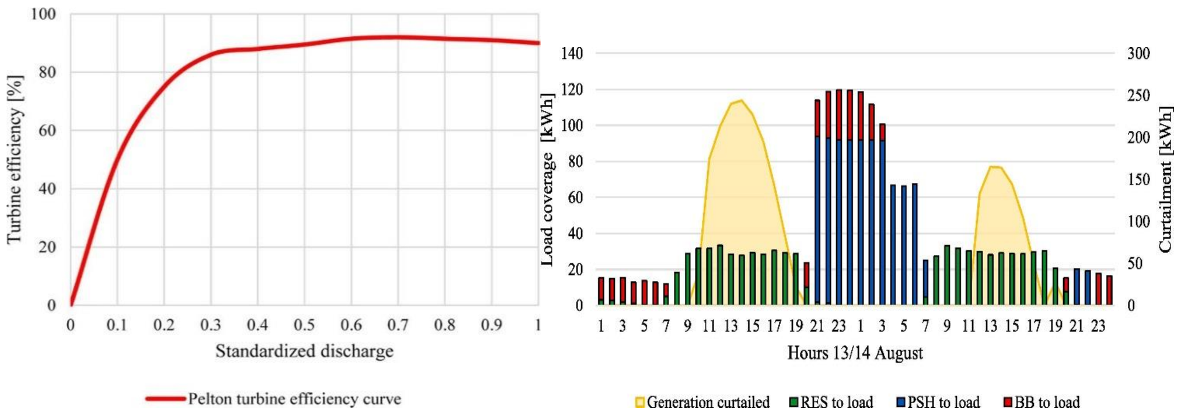


Figure 29 – Left: Pelton turbine efficiency curve [55]; Right: Example of Storage Dispatch in the study [54][3]

The constraint imposes that the PHES works at a minimum power equal or higher than a certain percentage of the maximum power. The value chosen is 20%, the same one adopted in the article by Guezgouz et al. [54], which allows having an efficiency higher than 75% as shown in Figure 29 left. Since the curve referred is a standard Pelton turbine curve, it was chosen to insert the value of the constraint directly in the code, without giving the possibility to the user to modify it on the GUI[4]. With this condition, as it can be seen from Figure 29 right, it will be possible to use the battery storage system even when the pumped hydro is not used due to the value of power needed being too low.

As showed in Figure 30, in the code, this condition for the discharge is placed after the dispatch algorithm: if the energy to be discharged from the pumped hydro storage is less than 20% of the discharge rate, then the cost of the PHES is increased to infinite (to avoid discharging) and the dispatch algorithm will be repeated; after performing the dispatch, the cost of pumped hydro storage is restored.

[3] RES to load, PSH to load and BB to load indicate respectively the renewable power, the PHES power and the battery power committed to serve the load.

[4] In the user's manual produced it can be found a reference to the lines of the code where this value is defined, and which can be modified.

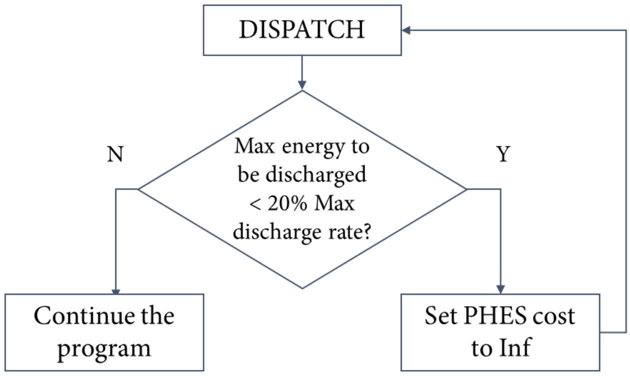


Figure 30 – Scheme of turbine efficiency condition

For the charge operation, the condition is placed in the section of storage update, after the dispatch, inside the same the condition for the charging: if the energy to be charged is lower than 20% of the charge rate, then the energy would not be stored in the PHES, but it will pass on to the BESS.

Threshold for off-peak hours

Then, a second condition was imposed considering the load curve. The objective of this constraint was to avoid that the storage would be discharged in the off-peak hours, when energy is normally cheaper, and demand is lower. Thus, if for a certain hour the demand is below a certain threshold, the cost of the PHES will be increased, so that it would not be used, being the cost returned to the original value after the dispatch is performed. This constraint was located at the beginning of the loop for each hour. However, the question of how to define this threshold remained.

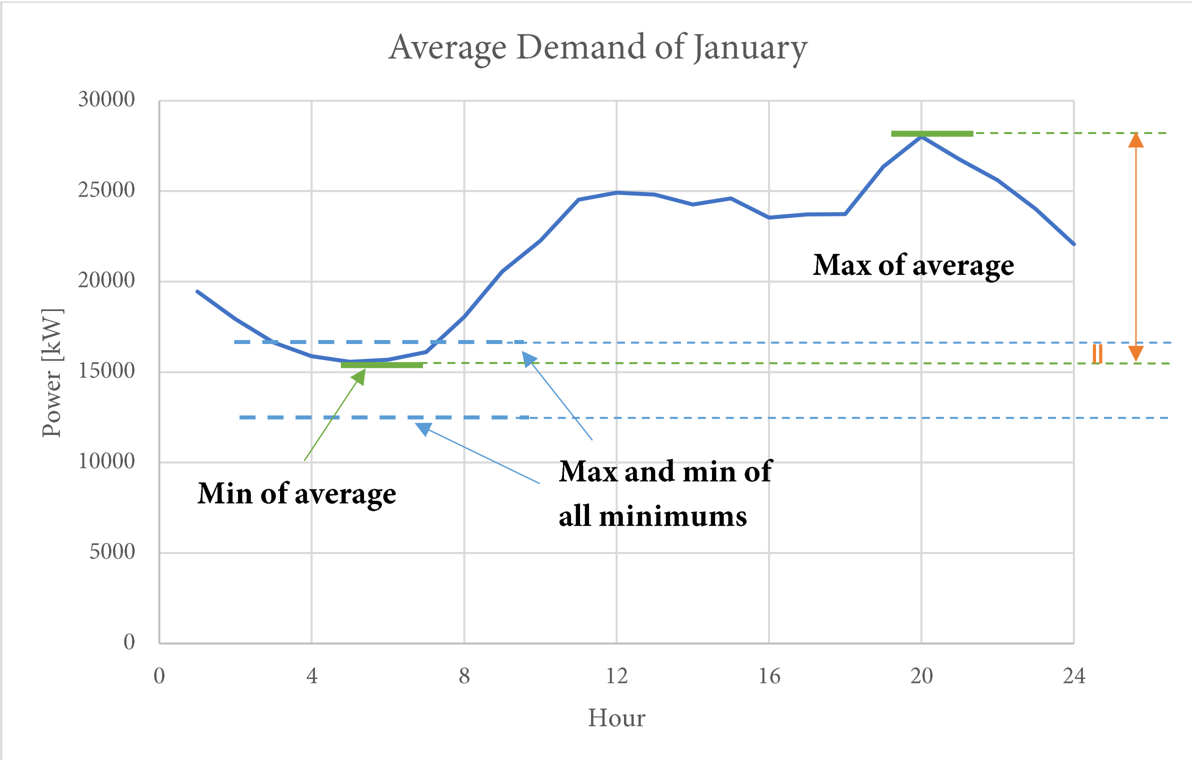


Figure 31 – Average demand of January with parameters considered for the calculation of the threshold

In Figure 31 the demand of an average day of January is represented, calculated as the average demand for each hour for the time interval selected, reporting also the respective minimum and maximum values. The absolute maximum and minimum demand values regarding all the minimum values of demand of all the days in January are also calculated, and will identify a range, as can be seen in the figure, which will prevent any errors or inconsistencies during days with values far from the average.

Accordingly, three methods have been identified for the calculation of the threshold.

- 1st method

$$T = Min\ of\ AV + \left(\frac{Max\ of\ MINs - Min\ of\ AV}{Min\ of\ AV} + tol\right) * Min\ of\ AV \tag{6.1}$$

- 2nd method

$$T = Min\ of\ AV + \left(\frac{Max\ of\ MINs - Min\ of\ AV}{Max\ of\ AV\ - Min\ of\ AV} + tol\right) * (MaxAV - MinAV) \quad (6.2)$$

- 3rd method

$$T = Min\ of\ AV + Range + Abs.\ tolerance \quad (6.3)$$

$$Range = Max\ of\ MINs - Min\ of\ AV \quad (6.4)$$

$$Abs.\ tolerance = 0.5 * (MaxAV - MinAV) - (Max\ of\ MINs - Min\ of\ AV) \quad (6.5)$$

Where:

$T\ =\ threshold$

$tol\ =\ relative\ tolerance$

$Max\ of\ Mins\ =\ maximum\ value\ between\ the\ minimums\ of\ each\ day$

$Min\ of\ AV\ =\ minimum\ value\ of\ the\ average\ day's\ demand$

$Max\ of\ AV\ =\ maximum\ value\ of\ the\ average\ day's\ demand$

Figure 32 shows the different results on the threshold according to the different methods of calculation.

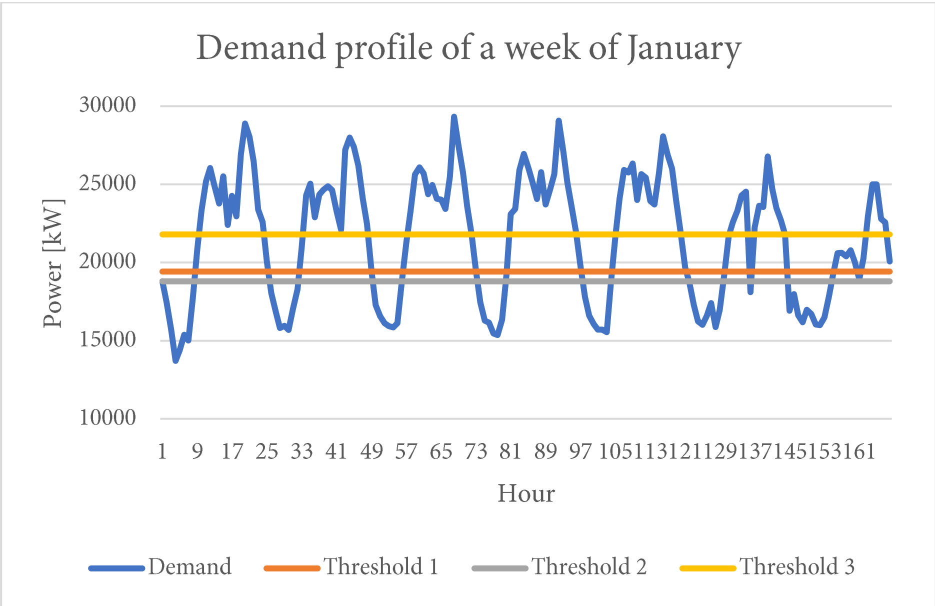


Figure 32 - Demand profile of a week of January with the three thresholds calculated

While, the first two methods present a relative tolerance that is chosen arbitrarily from 5% and 30% (in the absence of reference in literature), the third method uses an absolute tolerance defined in Equation (6.5). As can be seen from Figure 32, methods 1 and 2, with a relative tolerance of 20%, report similar values close to the daily minimum load, while method 3 englobes a higher value that covers most of the off-peak hours. For this reason, the third method has been preferred.

6.4.2. Storage in the optimization/history path addition

The idea to include the storage in the optimization process was first explored with a literature analysis (in section 2.2). Still, to include the storage in the optimization loop, a storage history path was needed to memorize all the values of the SoC for every possible path. In this way, the storage could be considered as a variable that would influence the choices of the optimization.

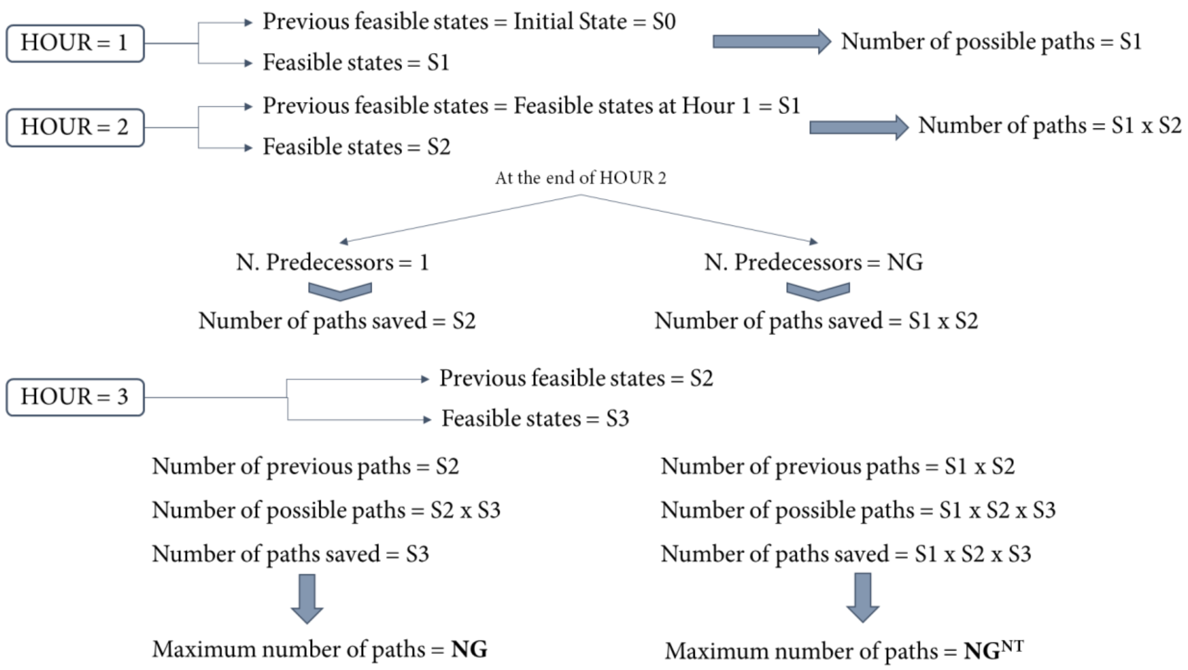


Figure 33 –Maximum number of paths calculation

As shown in Figure 33, for every hour, a number of feasible states are identified; then a new path is analysed for each feasible state combined with all the previous paths. The number of previous paths is the minimum number between the number of predecessors and the number of previous feasible states. To assess the implications of inputting the storage on the optimization algorithm, two limit cases have been considered:

1. the *Number of Predecessors* equal to 1; and
2. the *Number of Predecessors* equal to the maximum, which is the Number of Generators.

Considering that the maximum number of Feasible States is equal to the Number of Generators, the final result is that in 1. the maximum number of paths will be at the most equal to the maximum number of feasible states, which is NG, while in 2., assuming that for each hour the number of feasible states will be NG, the number of possible paths will increase at each hour, being NG^{HOUR}, and therefore at the last hour it will be equal to NG^{NT}, where NT is the number of time steps (number of hours), thus with an exponential number of paths to be analysed.

Regarding the storage, if a Storage History is to be created, a value for the SoC of the storage has to be saved for every possible path. The previous version of the code included the variable that contained all values of SoC of the storage inside the loop of the previous hours. Though doing so, the number of values that could be stored would be NG^{NT}, but the matrix created for that purpose was only NGxNGxNT, leading to an error. Creating an actual Storage History Path would make the computational time increase too much, especially for bigger systems, being NG^{NT} a number that would require a big amount of memory. Then, a partial and simple solution is to create it only for case 1. Although this choice erases the possibility to choose the number of predecessors, hence the possibility for the code to analyse more than one path at each hour, the creation of an effective storage history path is a much more relevant improvement. This modification does not have an evident effect on the results, but it definitely improves the algorithm and represents a step that goes in the direction of an optimization which includes the storage. Moreover, in all the tests done until now, both in this thesis project and in the previous ones, the parameter of *Number of Predecessors* was always assumed equal to 1, to avoid having long computational times. It has also been verified that when increasing this value, there are no relevant changes in the final results. In fact, what would really allow confronting more scenarios, would be the use of complete enumeration instead of priority listing, which is the real limiting element in the analysis.

In addition, it has to be accounted that, while the storage is considered as a generator in the dispatch, it is not considered as a generator in the search for the Feasible States for a certain hour; in fact, the minimum and maximum power for the storage are considered to be zero. This choice is due to the fact that the energy stored cannot be considered to satisfy the demand for a certain hour, because in that hour could be more convenient to operate the charge of the storage, therefore preventing the discharge. Even if the storage was to be considered to find the feasible states, this would have increased the number of possible combinations even more. As shown in the example of Figure 34, if at a certain hour, 4 feasible states are found, then 4 paths will be saved in the memory and therefore 4 values of SoC; at the next hour, a certain number of feasible states will be found for each value of SoC, and to each one will be associated a new path.

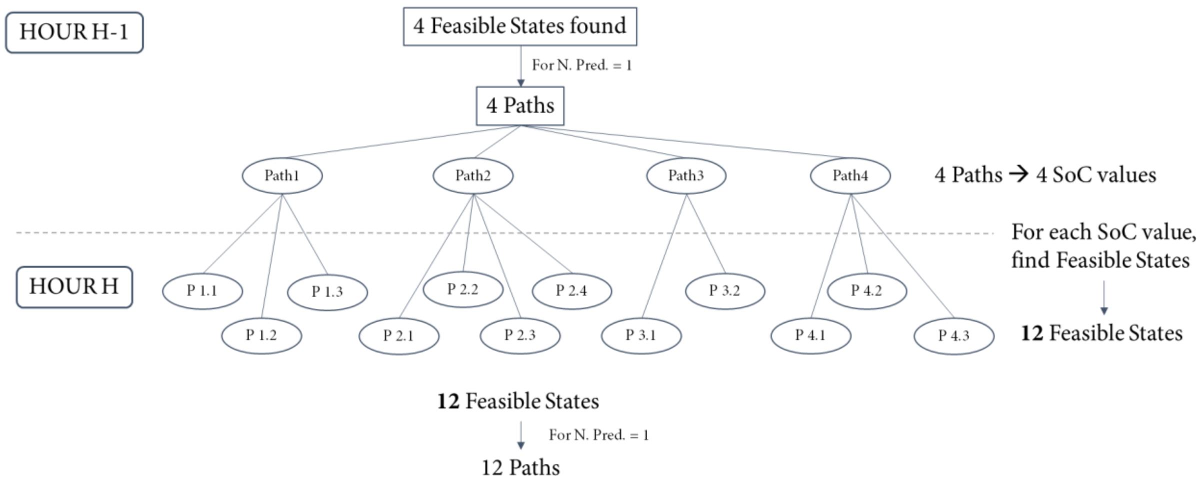


Figure 34 – Number of paths multiplication

This analysis has shown that, the storage operations still need improvements and that the real key solution to the problem could indeed be the inclusion of these operations in the optimization path. From the literature analysis, where most of the literature treats storage outside the optimization algorithm and looking at all the obstacles found in the implementation of this process, it was concluded that to include the storage in the optimization, radical changes are needed in economic dispatch algorithm used. However, that would require further study of electrical power systems, which goes beyond the possibilities of this thesis project, but it will be highlighted as a future possible improvement.

6.4.3. Dynamic pricing cost

After testing different methods to approach the storage functioning to the real operation world, the method found to best optimize decision was to use a dynamic pricing cost of the storage generators that can penalize or enhance some behaviours as reported by [28]. In the optimization performed with MATLAB's *fmincon* function, the objective function minimizes the cost function *F*, which is calculated as:

– for thermal generators:

$$F = \big(Ginc(i) * x(i) + Gnlc(i)\big) * Gfc(i) \tag{6.6}$$

– for renewables and storage:

$$F = Gfc(i) * x(i) \tag{6.7}$$

where *Ginc* is the incremental heat rate cost in (fuel unit/kWh), *Gnlc* is the no-load cost in (fuel unit/h), *Gfc* is the fuel cost in (€/fuel unit), *i* is the generator and *x* is the power committed of the generator in (kW).

As a result, the cost function will be modified making the cost of storage dependent on the SoC of the storage and adding a curtailment cost for the wind power production, in order to enhance the cost opportunity of charging when there is excess wind production (avoiding the curtailment).

Cost dependent on the SoC

This method is also adopted in many other studies ([11], [27], [29]) and has the objective to discourage the discharge of the storage when the SoC is low. The dependence of the cost on the SoC is linear, as shown in Figure 35.

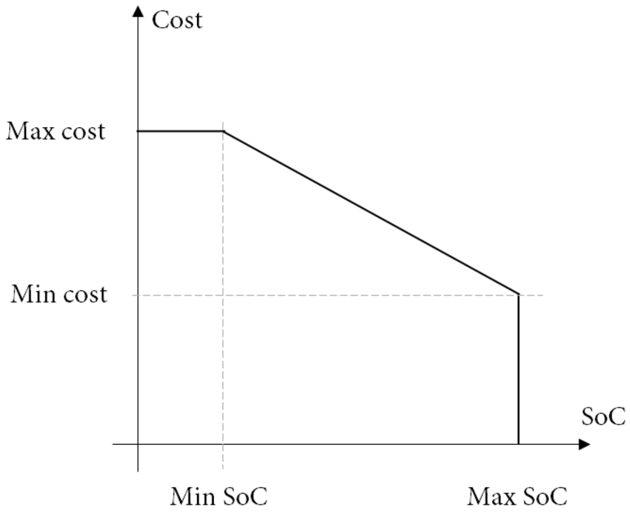


Figure 35 – Storage cost function

The Min cost is equal to the equivalent fuel cost (LCOE) of Storage, while the Max cost has to be less than the minimum cost of all the no-load costs of thermal generators. The cost function for the storage entries will be:

$$F = SoC\ cost(i) * x(i) \tag{6.8}$$

where the SoC cost is represented by the piecewise function:

$$SoC\ cost = \begin{cases} Max\ cost, & SoC \leq minSoC \\ \dfrac{Max\ cost - Min\ cost}{\min SoC - \max SoC} * SoC, & minSoC \leq SoC \leq maxSoC \\ Min\ cost, & SoC \geq maxSoC \end{cases} \tag{6.9}$$

Additional cost for wind curtailment

The penalization cost for wind curtailment enhances the wind power commitment in the dispatch, which was used in [28], [33], and it was decided to assume a curtailment cost of 150 €/MWh, as reported by [28]. The curtailment cost is then multiplied for the wind power curtailed, which is calculated as the difference between wind power forecasted and wind power committed in the dispatch.

$$Wind\ power\ curtailed = Wind\ power\ forecast - x(wind) \quad (6.10)$$

$$Additional\ curtailment\ cost = Wind\ power\ curtailed * Curtailment\ cost \quad (6.11)$$

$$F = Gfc(i) * x(i) * Additional\ curtailment\ cost \quad (6.12)$$

7 Case study: Madeira

To test the latest improvements and the flexibility of Vulcano tool, and trying to answer to the research hypothesis, it was decided to model a new case study.

7.1. Madeira Island and Energy System

Madeira is an island in the Madeira archipelago, which is situated in the North Atlantic Ocean, southwest of mainland Portugal. It is a volcanic island, with an area of 740.7 km^2 and a population of 262,456. The island is the top of a submerged shield volcano that rises about 6 km from the floor of the Atlantic Ocean. The archipelago of Madeira is located 520 km from the African coast and 1,000 km from the European continent. Madeira has many different bioclimates: based on differences in sun exposure, humidity, and annual mean temperature, there are clear variations between north- and south-facing regions; the islands are strongly influenced by the Gulf Stream and Canary Current, giving mild year-round temperatures. The economy is mainly based on tourism. [56] Figure 36 describes the energy consumption of Madeira archipelago in terms of electricity and primary energy, reflecting the economy of the region.

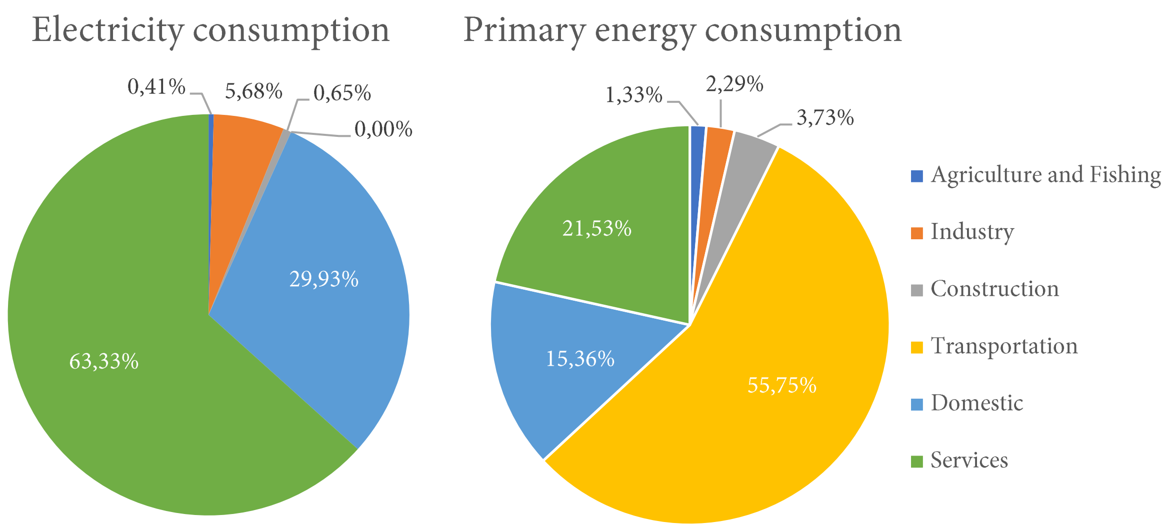


Figure 36 – Madeira Energy System [57]

Madeira electrical energy system is owned and managed by EEM (Empresa de Electricidade da Madeira) and is based on conventional thermal power plants and hydro plants, complemented by a solid amount of wind energy and steady growing solar energy production [58]. Madeira government, with the commitment in reaching 50% of production from renewable energy by 2020, invested in new wind and solar power plants, as well as in the modernization of already existing hydro power plants and pumped hydro storage system, together with a new battery storage system [59]. As of 2019, the commitment was renewed with the PNEC 2030 (Plano Nacional Energia e Clima) where the new target of reaching 80% of renewable electricity production by 2030 was set [60].

Table 12 shows the energy mix production of 2019, while the characterization of the energy system based on the energy source can be found in Table 13.

Table 12 – Energy in 2019 [61]

Energy produced in 2019		
	[GWh]	[%]
Hydro	44.1	5.2
Wind	94.2	11.1
PV	30.5	3.6
RSU	40.7	4.8
Thermal (Gas)	166.3	19.6
Thermal (Diesel)	473.4	55.8
Total	**848.4**	**100**

Table 13 – Madeira energy system for 2016 and 2020

Energy System	*2016*	*2020*
Generators [MW]		
Thermal (Natural Gas)	48.6	48.6
Thermal (Diesel)	12	12
Thermal (Fuel Oil)	150.6	150.6
Hydroelectric	24.49	39.49
RSW	4.8	4.8
Photovoltaic	18.8	78.8
Wind	43.3	61.3
Storage [MWh]		
PHES	22.2	22.2
BESS	0	10

Two typical daily profiles of demand and production are shown in Figure 37, respectively for a day in December and a day in June.

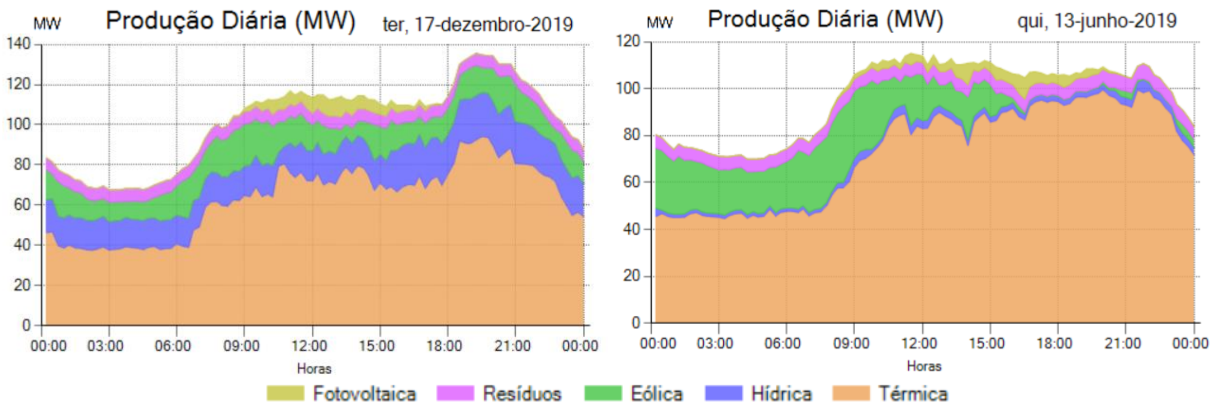


Figure 37 – Madeira daily electricity production in December and June 2019 [62]

7.2. Input data and assumptions

Simulations of Madeira Energy System were performed with two different data set, as characterized in Table 13, one referred to the 2016 asset and one referred to the 'future' 2020 asset, which includes plants built after 2016 or under construction.

7.2.1. Demand

Being in possession of the hourly values of energy production for the year 2016, the values of demand were calculated as 90% of the production to include the distribution losses. Regarding the year 2020, because no data was available, the demand was calculated increasing the 2016 values of a percentage obtained by the linear fitting of the total energy production from 2016 to 2019, as shown in Figure 38.

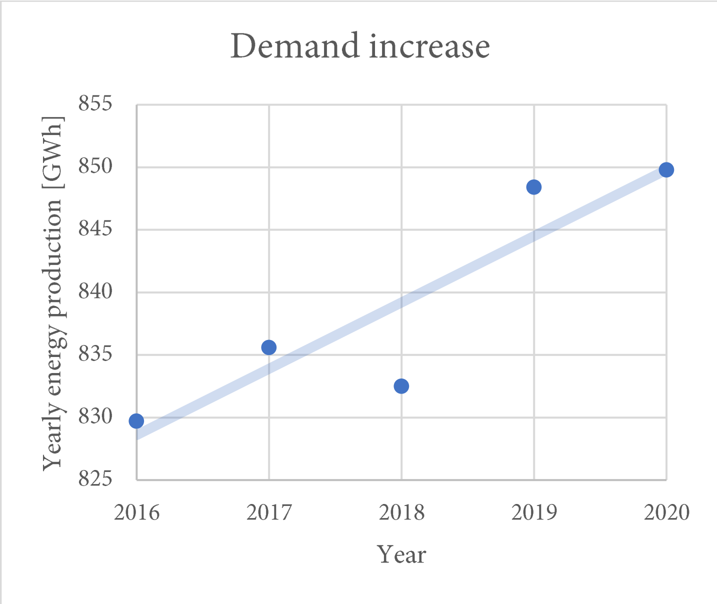


Figure 38 – Demand increase from 2016 to 2020 [61]

As a result, the demand for 2020 was increased by 1.165% with respect to the one in 2016.

7.2.2. Constraints

Madeira energy system presents several constraints already analysed by Rita in [22] which can be summarized in:

- Priority constraints: a minimum of thermal generators has to be always online and the renewable commitment has to follow the order hydro-solar-wind.
- Minimum power constraints: minimum power of generators have to be respected, one fuel oil plant has a minimum amount of energy to produce a year, there is a yearly contract regarding the supply of natural gas, that will consequently need to be used.
- Spinning reserve constraint: the spinning reserve has to be higher or equal than 1.2 times the power of the largest group online at a certain time.

These constraints, however, were not able to reproduce in the simulation due to technical limitations of the code, as explained further:

- It is not possible to force a generator to be always in the on-state with a specific feature; the only way to respect this constraint would be manipulating the cost, but this operation would alter the overall costs of the system;
- The tool has no way of defining an order of dispatch other than the cost, and because the renewables have zero cost the renewable priority cannot be defined;
- The constraint on the natural gas consumption would be particularly difficult to implement because in real operation this contract results in higher consumption of natural gas toward the end of the year, but Vulcano tool can simulate different lengths of time, this constraint would be difficult to insert;
- Spinning reserve can only be inserted as a percentage of the load, hence this definition is not allowed. Therefore, the simulations were performed with spinning reserve = 0%.

7.2.3. Data treatment and assumptions

The input data used for the 2016 simulations were obtained from [22], which collected it from Madeira energy provider (EEM). The PHES was added to the data set, which had not been tested because of the issues found in the storage operations.

Regarding the renewable sources' availability, the wind speed was obtained from NASA Database [47], while the solar power output was calculated with Ninja Renewables web application [46].

The simulations were made with "High Renewable Energy System" mode and the VRE allowed penetration factor was assumed equal to 100%. All ramp up/down rates were inserted in the toolbox as infinite, given that the time step for the simulations is one hour and the ramp-up rates indicated resulted in ramp-up times much smaller than 1 hour.

Since the Madeira energy system is of a larger dimension, with multiple generators for each technology, the generating data have been simulated in two different ways:

- One dataset presents the generators aggregated by energy source;
- The other dataset presents the generators grouped for power plant.

7.3. Results

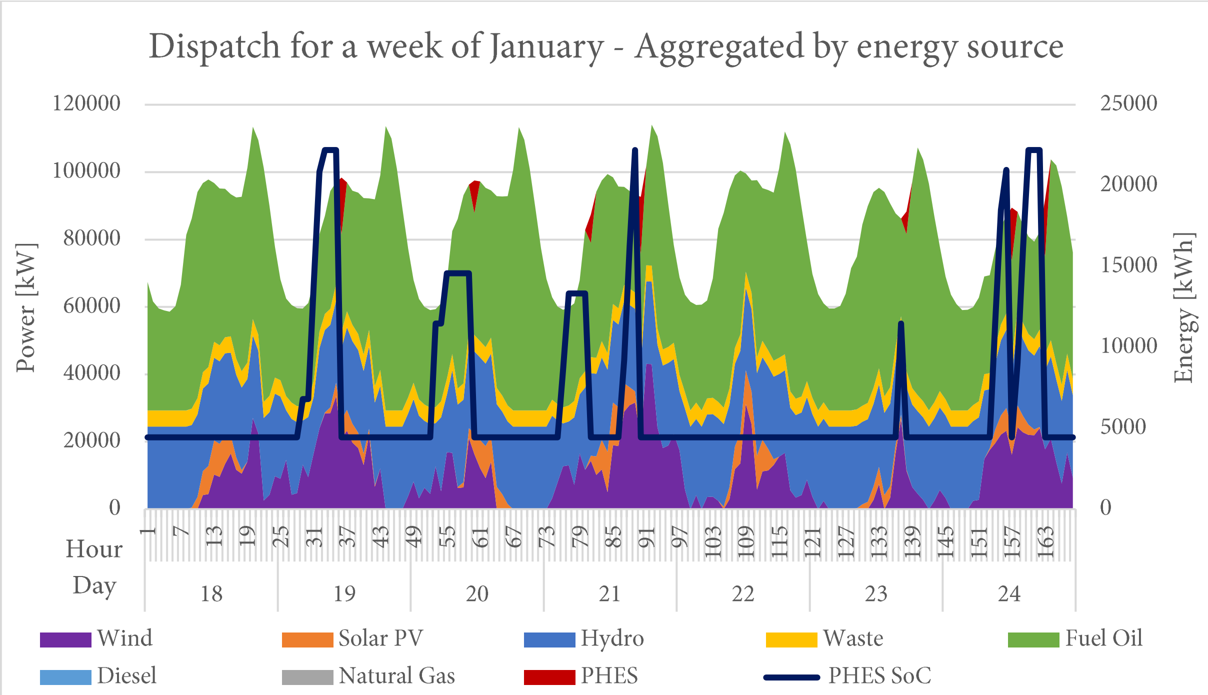
Simulations were performed for two weeks of the year, one in January and one in June, both for the energy system of 2016 and 2020.

2016 Energy system

Figure 39 shows the economic dispatch for the week of 18^{th} to 24^{th} of January (Monday to Sunday), in both configurations of the data set.

The distribution of energy production results similar in the results of the two simulations, with the exception of the storage dispatch and SoC evolution. In fact, in the first case (aggregation by energy source), the PHES is discharged more times during the local peak hours of the day (i.e. morning peaks), while in the second case (aggregated by power plant), the discharge happens only in two days, however in the highest peak hours of the day (hour 19-20).

Regarding the SoC of the PHES, it can be noticed that in the first case the level is usually at the minimum and in the hours of VRE excess is charged, being then discharged in a short time or at the next hour. In the second case, instead, when the storage is charged, it stores the energy until the peak hour, when it is discharged to the minimum. Yet in the last four days, it is only charged until the maximum capacity, since the demand peaks are lower.



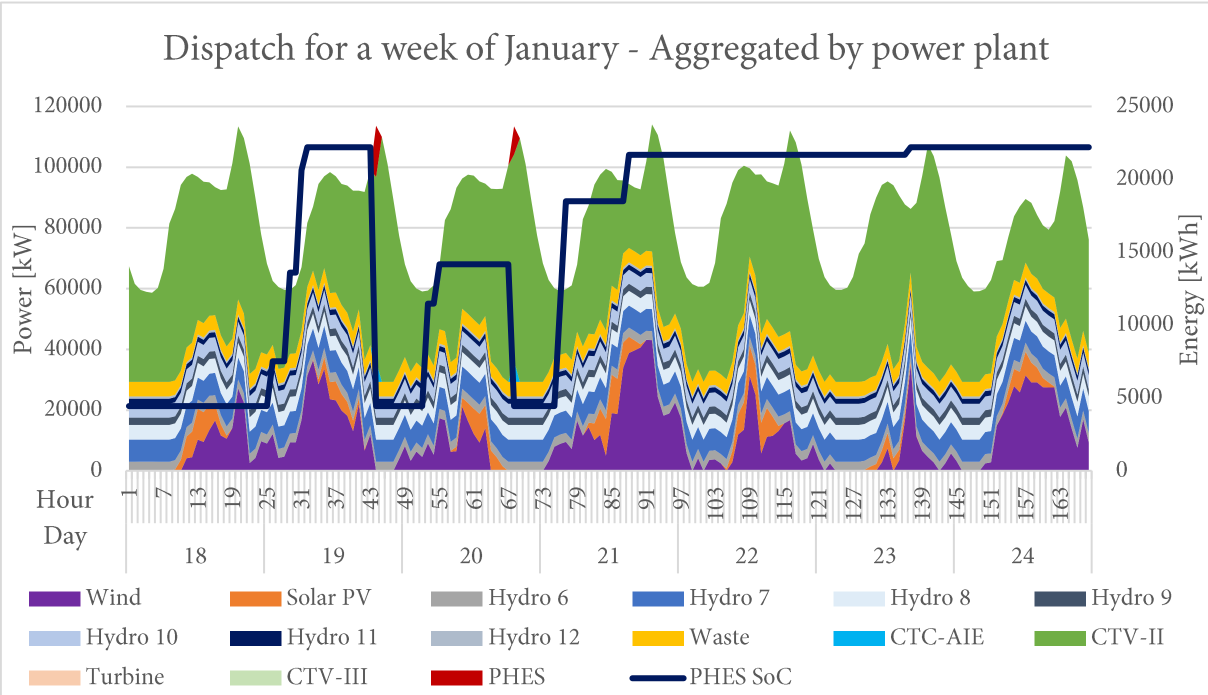


Figure 39 – Dispatch on a week of January in Vulcano for two configurations of data

The results of the two simulations are very close as the values of the error in Table 14 demonstrate, except for the PHES. This similarity is partially due to the fact that the thermal production is almost entirely provided by the CTV-II power plant fuelled with Fuel Oil, while the other Fuel Oil plant, CTC-AIE, is only committed for two hours at the minimum power.

Therefore, the Fuel Oil production in the first case is almost correspondent to the CTV-II plant production in the second case. The Diesel Turbine and the Gas-fuelled plant, CTV-III, instead, are never committed.

Table 14 – Energy dispatched in a week of January

Energy dispatched	*Hydro*	*Wind*	*Solar*	*Fuel Oil*	*Waste*	*PHES*
Aggregated by energy source [kWh]	3945931	1717564	343421	7241571	804320	91089
Aggregated by power plant [kWh]	4114319	1821039	343739	7032282	806400	26117
Error [%]	**4.09**	**5.68**	**0.09**	**2.98**	**0.26**	**248.77**

A third simulation was done with a different configuration: all the single generators of each power plant were modelled as individual. Table 15 contains the average values of renewable penetration for the two configurations analysed and for the third simulation that was done. The renewable penetration increases as the generators are less aggregated, as expected because the constraints on minimum power of thermal generator leads to a higher thermal power committed. The configuration with individual generators could be the one that can better reproduce real operation because it describes the commitment of each unit, but modelling systems like the one of Madeira, with 45 generators, will increase the computational time and the complexities in the final data, which will be more difficult to analyse. Because the increase in the percentage for the third case is only of 1.6%, the analysis of the system with the individual generators configuration was not considered worth.

Table 15 – Average renewable penetration for a week of January

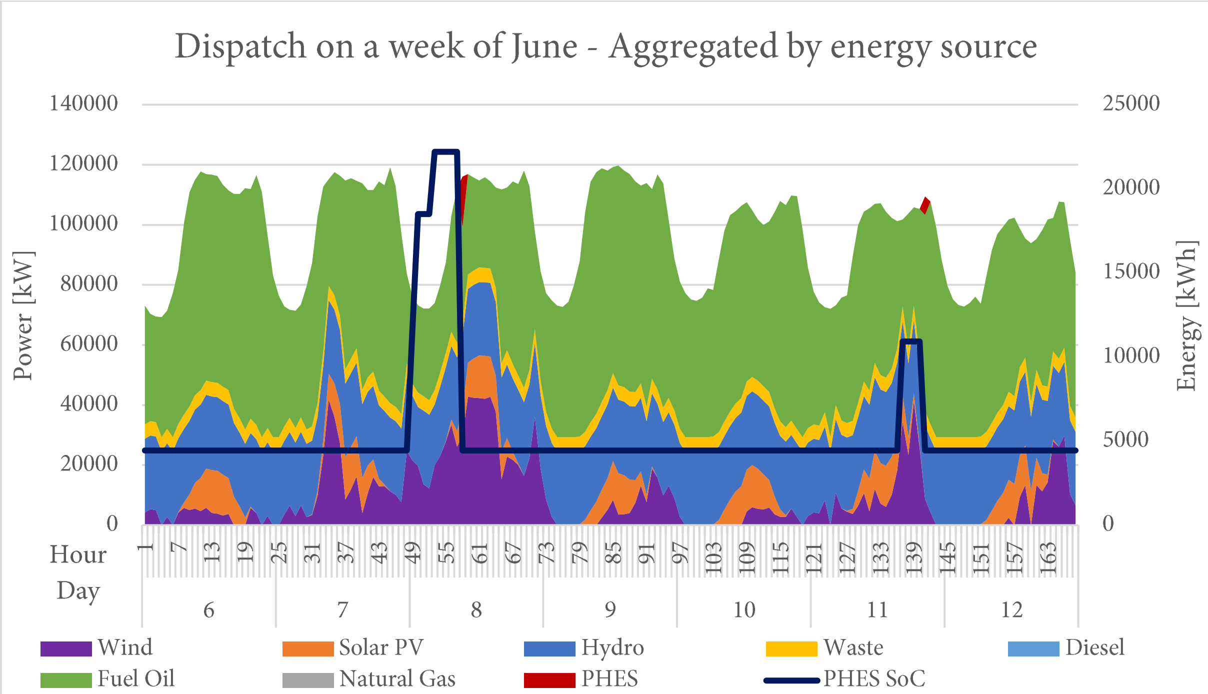
Renewable penetration – January	
Aggregated by energy source	42.69 %
Aggregated by power plant	44.86 %
Individual generators	46.15 %

In Figure 40 the results for the simulations in the week from 6th to 12th of June (Monday to Sunday) can be found. During this period of the year, the production from wind energy is less consistent than in winter, while the solar production is much higher in terms of peaks reached during the day and number of working hours, however leading to higher overall renewable production than in the week of January, as can be seen in Table 16.

Table 16 – Average renewable penetration for a week of June

Renewable penetration – June	
Aggregated by energy source	39.51 %
Aggregated by power plant	39.80 %

Comparing the two cases with different configurations of the dataset (Figure 40), the same considerations of the previous simulations can be applied. In this case, the difference is that with the generators aggregated by power plant the storage is never discharged. This difference is due to the fact that in the first configuration the storage is discharged at hour 10 of the day 8th (hour 58) as can be seen from Figure 40, while this does not happen in the second configuration. In the first case the storage is discharge because in the priority list of the generators the PHES is one of the most convenient generator, and its position is definitely before the one of the diesel and gas generators. In the second configuration, because there is another fuel oil plant similar to the one committed, this will probably be in the priority list in a position higher than the one of the PHES, avoid its discharge. It can also be noticed in Table 16, how the difference in renewable penetration is really small between the two configurations.



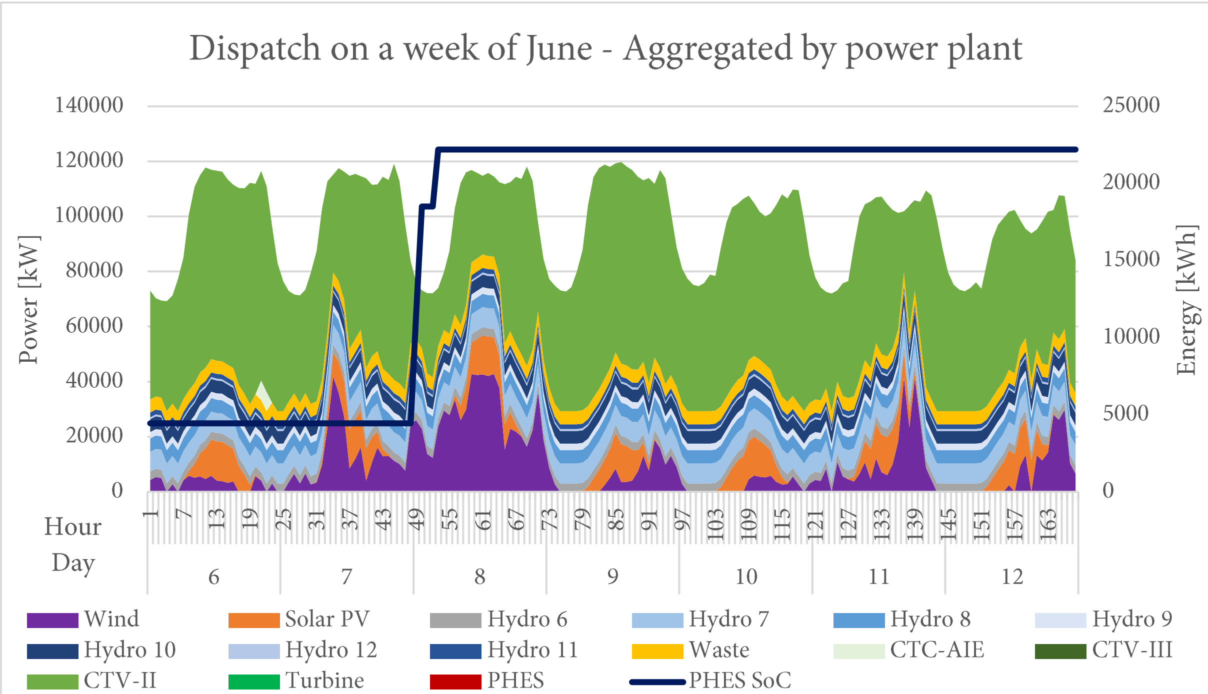


Figure 40 – Dispatch on a week of June in Vulcano for two configurations of data

2020 Energy system

For this set of simulations, the results are shown in Figure 41. In this case it was chosen to show only the results of the simulation with the configuration of data aggregated by power plant, being this configuration more accurate and because the scope of the 2020 simulation was not to analyse the difference between the configuration, but instead to analyse a high renewable penetration system and its difference with the 2016 system.

These simulations were done with a projection of demand for 2020 as shown in section 7.2.1, but with standardized for solar radiation and wind speed.

The overall behaviour has not changed, but it can be noticed in Figure 41 how, with additional renewable power plants, the hours in the middle of the day, when the solar PV production is at the maximum, the load is completely satisfied by renewable energy (including also the waste power plant). In June, the period of time during the day with 100% renewable production is longer than in January, being the solar PV production greater in power and in number of hours with respect to January.

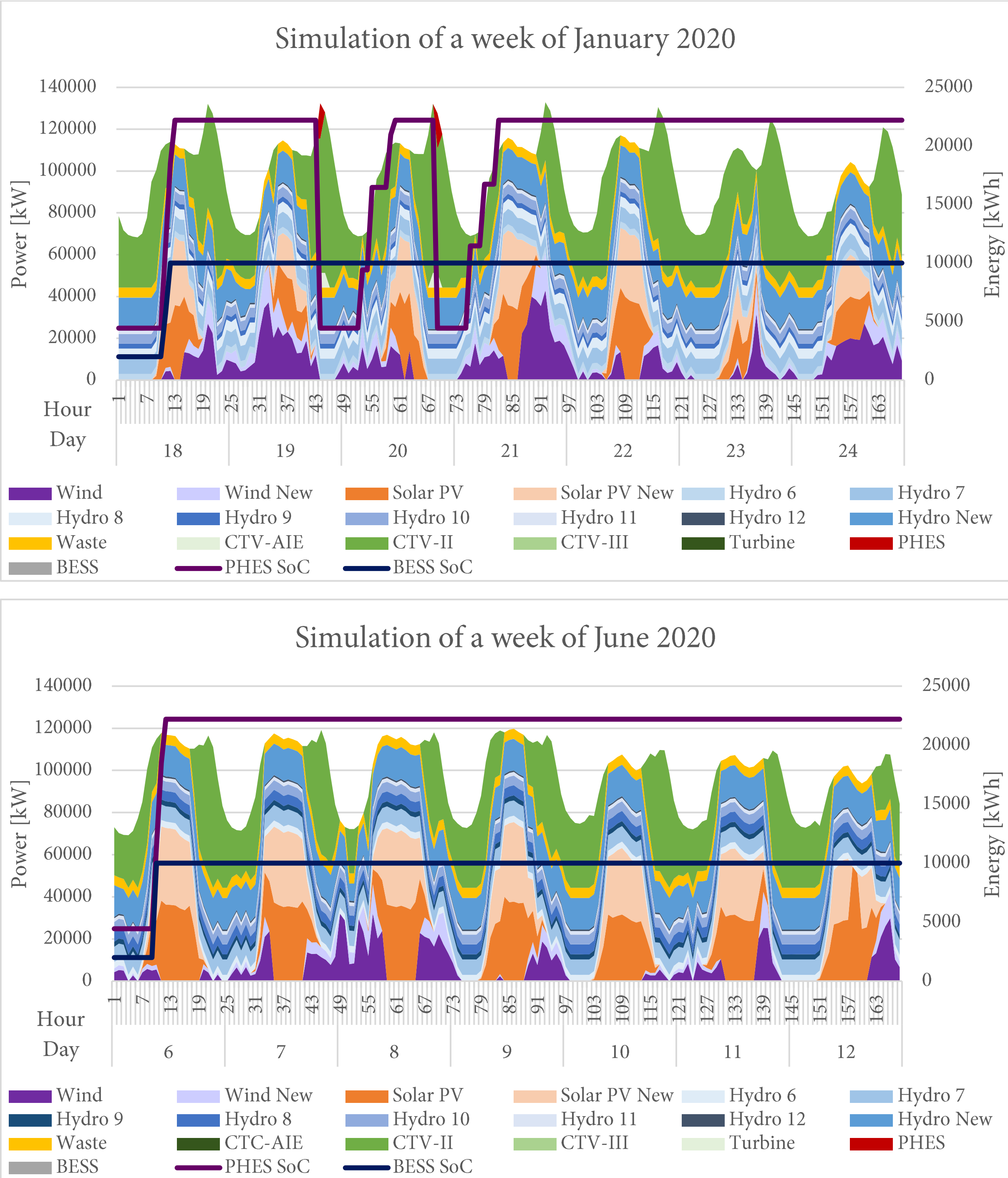


Figure 41 – Simulation of the dispatch on a week of January and June in Vulcano for the year 2020

As it can be noticed from Figure 41, there is a sudden drop in the production of solar energy during the central hours of the days, the same hours were 100% of renewable production is reached. Analysing the data obtained from the simulations, in fact, it is found that, 19% and 31% of the renewable production is curtailed, respectively, for the week of January and June.

This means that with this power plants' configuration of the system larger energy storage systems are needed since as seen by the SoC it is already full

Table 17 contains the average percentage of renewable penetration for the two weeks analysed. With respect to the system of 2016, it can be noticed that the percentage has increased in June with respect to January because of the higher capacity of the solar power plant.

Table 17 – Average renewable penetration for a week of January and June in 2020

	Renewable penetration
January	65.63 %
June	72.64 %

8 Conclusions

The analysis and work carried out in this research project started from the thorough analysis of the Vulcano modelling tool and the identifications of its problems. A great number of simulations were run and compared to the simulations results obtained with the commercial tool HOMER. This comparison allowed to clarify the reasons behind the problems and to reveal new problems. While solving some of the identified issues, the ESS integration in the tool and its operations were investigated, representing the majority of the problem. Some solutions were adopted, and new simulations were carried out to test the changes made to the tool.

The study proposed in this thesis did not have the objective of analysing the two islands' energy systems, but to analyse the functioning of the tool, which allowed to identify the current problems, some of which were solved, while some other identify future possible developments. Nevertheless, many of the modifications and improvements made to the code were not initial objectives but have been set during the course of the project, when the analysis of the tool showed several problems in the code to be solved.

Considering the research questions posed in section 1.2 it can be concluded that self-built models can be versatile to model different energy systems. In fact, Vulcano is indeed a valid modelling tool and that can effectively reproduce the dispatch operations of a system, both in case of low and high renewable penetration systems, similarly to software like HOMER and with further realistic features related to operation however with some data treatment.

To accommodate the increasing penetration of renewable sources modelling tools, need to adapt. This means that in some cases the calculation of a certain parameter or the choice of a condition in the algorithms has to change. It was found, for example, that in Vulcano the way the parameter considered to create priority listing was calculated, was bringing to a curtailment of RES, while prioritizing thermal generators. At the same time, it has to be considered that storage systems are still under deployment and development, but the importance of ESS in increasing hybrid renewable energy systems is growing and so is the necessity of tools that are able to model. Regarding this aspect, there are less information in the literature and also the tool still needs improvements. In fact, even if some solutions have been developed with satisfying results, these are still not close enough to real operations. Vulcano tool is, in conclusion, a useful tool for preliminary operational analysis of a system and for the evaluation of technically and economically feasible and convenient solutions that can be adopted in an isolated microgrid system.

Along with some minor bug's fixes the major modifications that were made to the code can be resumed as follows:

- implementation of the function to save results in an excel file;
- addition to the GUI of the possibility to choose between a "High Renewable Penetration System" and a "Low Renewable Penetration System";
- development of the possibility to input the wind speed instead of the wind power output for Custom Length Simulations;
- improvements to the storage:
    - inclusion of geothermal and waste energy excess in the energy to be stored;
    - calculation of the excess energy to be stored at each hour;
    - addition of minimum and maximum SoC limits;
    - possibility to define as a constraint the minimum thermal share instead of the maximum renewable penetration factor;
    - condition on PHES charge/discharge operation with a minimum charge/discharge rate;
    - definition of a threshold to avoid the discharge of the ESS during off-peak hours;
    - creation of a storage history path to improve the algorithm for storage integration in the dispatch;
    - modification of the definition of storage cost into a dynamic cost that changes at each hour.

8.1. Possible improvements and future work

Of all the problems of the tool, some of them were already known before the beginning of this project, while other were identified during the work. Although many improvements were made to the code, there are still some unsolved issues, that can be analysed in a future development of the tool.

- Implementation of the possibility to input more than one type of PHES and BESS, however commercially available tools only allow one storage item per technology;
- Include the storage operations inside the optimization, so that the charge and discharge operation would be more effective and would actually increase the renewable penetration. This would also make the decision of which ESS should be charged and discharged first, based on which type is more effective for the use needed based on the characteristics and on the costs;
- Allow systems with 100% renewable production, either allowing the system to have zero costs or making the cost of renewables mandatory;
- Allow the thermal generators of the same size to have a different values of power.

Although this tool is thoroughly able to reproduce the unit commitment of generators in an energy system, it is less able to accommodate all the additional constraints and requirements that the increasing penetration of renewables and presence of storage systems demand. In this perspective the whole structure and of the tool should be reviewed to understand if a radical change of algorithm is needed or if the current one can be adjusted to reproduce and simulate the new, rapidly-evolving energy systems.

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Annexes

Terceira Energy System

Belo Jardim Thermoelectric Power Plant			
Generator	*Fuel*	*Rated Power [kW]*	*Minimum Power [kW]*
1	Diesel	3128	1500
2	Diesel	3128	1500
3	Diesel	3000	1500
4	Diesel	2860	1500
5	Fuel Oil	6100	3000
6	Fuel Oil	6100	3000
7	Fuel Oil	6100	3000
8	Fuel Oil	6100	3000
9	Fuel Oil	12300	6000
10	Fuel Oil	12300	6000
Wind Power Plants			
Power plant	*Number of WT*	*Power [kW]*	*Total Power [kW]*
Serra do Cume (EDA)	10	900	9000
Serra do Cume (CAEN)	4	900	3600
Hydro Power Plants			
Power plant	*Power [kW]*		
Cidade	264		
São João de Deus	448		
Nasce Água	720		
Total	1432		
Other Power Plants			
Power plant	Power [kW]		
Pico Alto Geothermal	4000		
Residual Solid Waste	2500		

Simulation results of section 5.2.2

		Fuel Oil			Wind		Hydro	Geothermal	Waste
		Gen. 5	Gen. 6	Gen. 9	EDA	CAEN			
Vulcano	Energy [kW]	0	0	209232	86813	40012	34368	76107	40141
	Working hours [h]	0	0	24	24	24	24	24	24
HOMER	Energy [kW]	66043	35999	0	150744	60297	29218	96000	60000
	Working hours [h]	21	12	0	24	24	24	24	24
Error [%]	Energy production	100.0	100.0	100.0	42.4	33.6	17.6	20.7	33.1
	Working hours	100.0	100.0	100.0	0.0	0.0	0.0	0.0	0.0

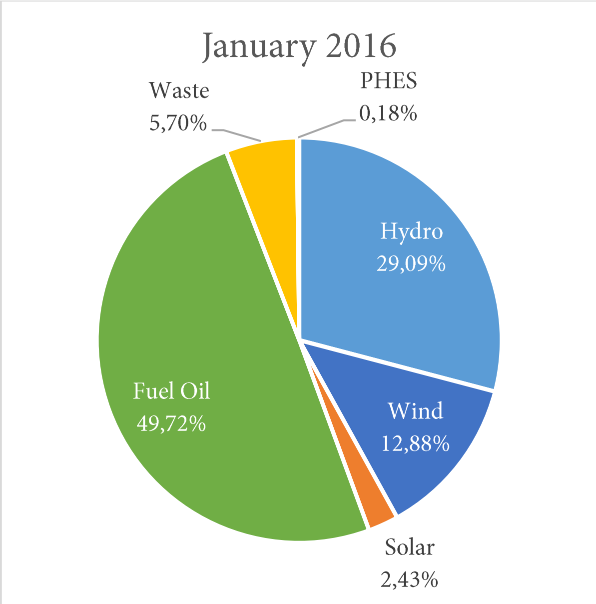
		Vulcano	Homer	Error [%]
PHES	Energy stored [kWh]	42100	19792	112.7
	Energy dispatched [kWh]	0.0	9690	100
	Average SoC [%]	70.1	9.3	656.1
	Peak of energy content [kWh]	42100	5868	617.4
BESS	Energy stored [kWh]	13500.0	0	100
	Energy dispatched [kWh]	0	0	0
	Average SoC [%]	65.3	0	100
	Peak of energy content [kWh]	13500.0	0	100

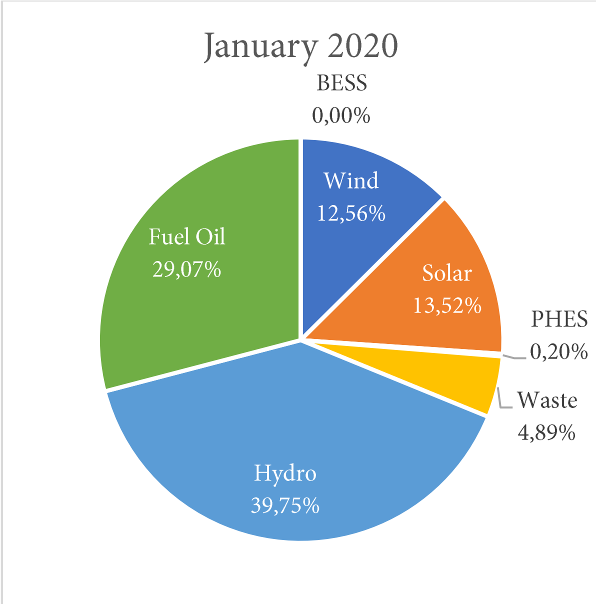
Madeira Energy System

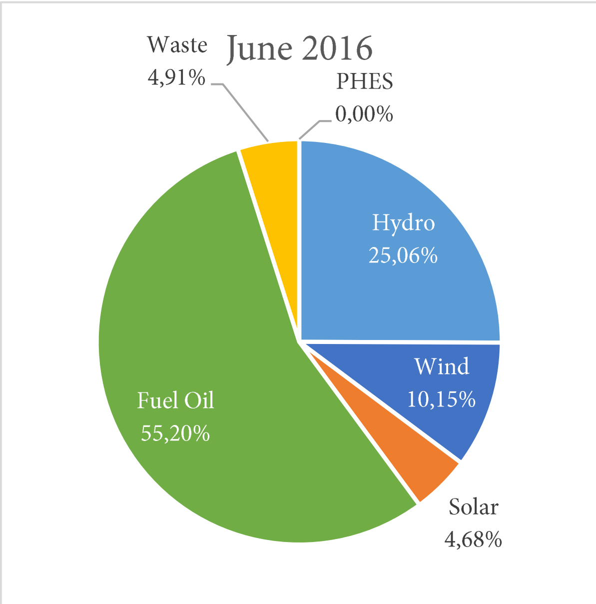
Thermoelectric Power Plants			
	P_{min}	P_{max}	*Fuel*
CTC-AIE 1	21000	36000	Fuel Oil
CTC-AIE 2	21000	33600	
CTV-II 1	28000	34000	Fuel Oil
CTV-II 2	35000	47000	
CTV-III 1	24000	45000	Natural Gas
CTV-III 2	0	3600	
Turbine	0	12000	Diesel
	$P_{nominal}$ *[kW]*		
Hydroelectric Power Plants			
Ribeira da Janela	3000		
Serra d´Agua	4800		
Calheta	4570		
Fajã da Nogueira	2400		
Calheta de Inverno	7300		
Socorridos	24000		
Santa Quitéria	1700		
Terça	720		
Calheta III (2020)	15000		
Waste Power Plant			
Meia Serra (MSR)	4800		
Solar PV Power Plants			
Enersistems 6x1000	6000		
Paul Solar 2x1000	2000		
PV Loiral 6x1200	7000		
Mini e micro production	3800		
PV1 (Grandes Dimensões) (2020)	5000		
PV2 (Grandes Dimensões) (2020)	5000		
PV3 (Grandes Dimensões) (2020)	5000		
PV4 (Grandes Dimensões) (2020)	5000		
Distribuida Grande dimensão (2020)	15000		
Distribuida Média dimensão (2020)	15000		
Distribuida Pequena dimensão (2020)	10000		
Wind Power Plants			
ENERGÓLICA	3000		
ENERGÓLICA	900		
ENEREEM Actual	3300		

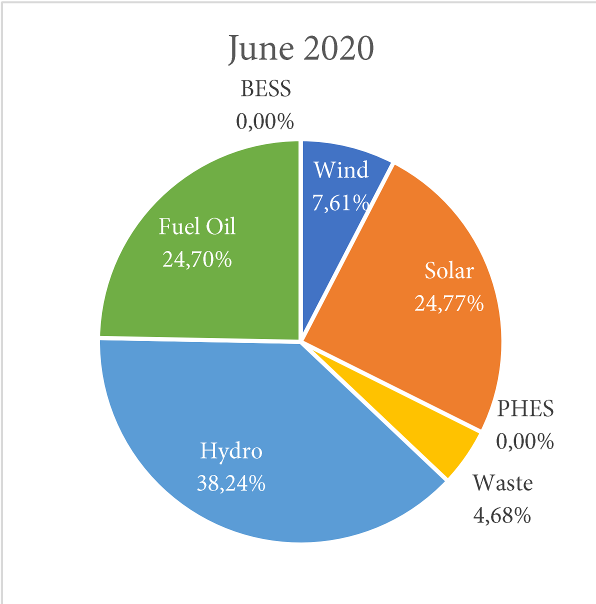
WindMad (Q. do Lord)	2550
ENEREEM Pedras	10200
ENEREEM Loiral I	5100
ENEREEM Loiral II	6000
Preform Fonte do Juncal	6000
Perform Norte	6000
Perform antigos	2640
Parque Eólico 1 (2020)	9000
Parque Eólico 2 (2020)	9000

Madeira simulation results









	2016		***2020***	
	January	*June*	*January*	*June*
CO2 Emissions [kg]	3772713	4750196	2616701	1896832
Total cost [€]	265672	334429	184797	133973
Fuel Consumption [L]	1139792	1435105	790544	573061