UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master’s Thesis

SPINNING RESERVE PROVIDED BY RENEWABLE ENERGY SOURCES

Author: **María del Carmen Prats Soriano**
Supervisor: **Lukas Sigrist**

Madrid, July 2019

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Foreword

This thesis is written as completion to the Official Master's Degree in the Electric Power Industry in Universidad Pontificia Comillas, during the course 2018/2019. The topic of this thesis, *Spinning reserve provided by renewable energy sources*, falls within the scope of the master's field because an economic evaluation of the profitability obtained by allowing renewable energies to provide spinning reserve is performed. Moreover, the subject requires an understanding of the regulation of the electric system in the Spanish islanded territories.

With this project, our university stage ends and, at this point, gratitude is the main emotion that stand out.

I could not be grateful enough to the University of Navarra for the four years I spent in San Sebastian, struggling with the Engineering degree at the same time as I took the first steps in the world of adulthood. Flying away from home is never easy, but Tecnun, the School of Engineering of the University of Navarra, became a second family since the very first moment.

After graduating in Electrical Engineering, ICAI (School of Engineering of the Universidad Pontificia Comillas) gave me the opportunity to specialize in the electricity sector with the combined master programme in Industrial Engineering and in the Electric Power Industry. Besides the pride of studying in the university in which my father graduated, ICAI meant opening new doors and getting closer to the goals I had been dreaming to achieve: not only I owe gratitude to the University, but also to Iberdrola, who has granted me one of their Master Scholarships in the 2018-2019 academic year and, thanks to this grant, has also given me the opportunity to start this new stage in a referent company of the electricity sector.

However, when I look backwards, all that comes to my mind are people. I would not be who and where I am without all the people that have stood next to me throughout these years. Thank you to all my professors, for the patience and fondness they have put in our education and all the efforts they have made to make sure we understood everything and made the most of the classes and thanks, especially, to Lukas, for supervising this Master Thesis and helping and solving my doubts always with the most positive and caring attitude. To my friends from Tecnun and ICAI: it has been a pleasure to learn, share thousands of doubts and study hours in the library (and, of course, coffees, dinners and beers) and laugh at our own stress together. To my friends from my homeland, Ibiza, that have always been by my side although we are all studying and working in different cities and with whom always feels like it was yesterday when we last saw each other, even though it has been ages.

And, of course, a big thank you to my family, who has brought me to where I am and has always raised and supported me to be who I am and give my 100%. Even when I thought my dreams where impossible to achieve, they have always kept believing in me. Thank you to my parents and siblings, but also to my grandmother, aunts and cousins. It is easier to fight for your goals when you have all this support. I would not be able to conclude without remembering those who are no longer with us. I hope part of all the happiness I feel right now goes up there and you can share this moment with us.

Thank you to you all.

Abstract

In the recent years, penetration of renewable energies in the system has been growing. However, renewable resources are often curtailed due to stability reasons. The uncertainty that this type of generation entails, together with the fact that renewable energies don’t provide inertia to the system drives the system operator to reduce the renewable input in order to maintain thermal groups connected. This has a greater impact on isolated systems, where there are few thermal generators in charge of providing the whole demand and wind penetration implies, therefore, a higher share of the consumption.

Thereby, insular electrical systems are especially sensitive to imbalances between generation and demand. A generation deficit causes the frequency to deviate from its nominal value and fall. The increase in the penetration of renewable energies amplifies this problem due to its intermittent nature and to the fact that renewable energies do not participate in the control of frequency. In order to rectify the deviation between generation and demand, a spinning reserve is required. In this regard, regulation affects differently the Spanish mainland and the isolated systems (Canary Islands, Balearic Islands, Ceuta and Melilla). Currently, the upward spinning reserve covers the loss of the largest group or the expected wind generation and at least half of the upward reserve in the case of the downward reserve. Dynamic response of the system is usually not evaluated in the spinning reserve criteria.

In this context, allowing renewable energies to provide spinning reserve would increase their penetration in the system, decreasing the dependency on thermal generators in isolated systems and satisfying the demand with clean energy resources. In consequence, this Master Thesis aims at determining whether it is economically profitable to enable wind energy to provide spinning reserve, increasing the renewable energies penetration without causing stability restrictions.

To this end, a model of the economic operation of islands has been developed, that allows simulating the unit commitment of island systems. This model has been applied to two Spanish isolated power systems: the islands of La Palma and Gran Canaria. Different scenarios have been simulated, varying the renewable generation profile and considering both that RES are not allowed to provide reserve and RES are enabled to provide reserve. Total costs for the dispatch have been obtained for each simulation performed.

From the results obtained, it has been shown that allowing renewable energies to participate in the spinning reserve brings high benefits to islanded electric systems, as system costs are lower for any scenario when renewable energies actively participate in the ancillary services. However, for the simulations in both islands it has been observed that providing reserve by means of wind generation only makes sense for very high wind penetration scenarios.

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1. Introduction and motivation

1.1. Motivation

In the recent years, penetration of renewable energies in the system has been growing. However, renewable resources are often curtailed due to stability reasons. The uncertainty that this type of generation entails, together with the fact that renewable energies don't provide inertia to the system drives the system operator to reduce the renewable input in order to maintain thermal groups connected. This has a greater impact on isolated systems, where there are few thermal generators in charge of providing the whole demand and wind penetration implies, therefore, a higher share of the consumption.

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1.2. Regulatory framework of the Spanish Isolated Power Systems [23][24]

As previously stated, the regulatory framework is different for the Spanish mainland and the insular and extra-peninsular electric systems, which include the Canary Islands, the Balearic Islands, Ceuta and Melilla, and are known as SEIE for its acronym in Spanish (Sistemas Eléctricos Insulares y Extrapeninsulares). Ceuta and Melilla constitute two isolated electric systems, while both archipelagos have several subsystems: the Canary Islands are composed of six independent systems (Gran Canaria, El Hierro, La Palma, Gomera, Tenerife and the interconnected islands of Lanzarote and Fuerteventura) while the Balearic Islands nowadays form two subsystems (Mallorca-Ibiza-Formentera and Menorca). At the same time, in the case of the Balearic Islands, Mallorca is interconnected with the Iberian Peninsula. However, this territory is still considered isolated as the capacity of the interconnection does not provide enough commercial capacity.

Therefore, the size and isolation of these systems together with the scarce interconnection capacity determine that the SEIE face a different situation than the peninsular territories, highlighting seven main points:

1. They are small isolated systems with generating groups that are much smaller than those in the Iberian Peninsula. This means that the capability of supplying the demand rely on less groups and that, in case of failure, less generators can respond to the system needs. Also, economies of scale are not exploited as they are in the continental territories (having less power plants with a bigger

size would endanger the reliability of the system in case of failure of that generation plant) and, therefore, generation becomes more expensive.

2. Technologies used are limited to small and medium conventional thermal plants, as there is no possibility of installing a nuclear or a big hydro power plant, due to the size of these systems and the unavailability of the energy source needed.
3. Reserve margins are bigger than in the Iberian Peninsula. Again, this is due to the small number of groups generating: the responsibility that each group has in case of any kind of failure is bigger than in the Peninsula where this responsibility is shared between a larger number of generators.
4. The SEIE are usually limited in territory. There is not enough space to build several power plants and transmission infrastructure, so power generation must be grouped in less plants. As previously explained, this means an increase in the difficulties that the grid faces when any failure in the network or the generators occurs.
5. Because of the fragility of these systems, security of supply must be a priority over costs.
6. Climatology, orography and seasonality of the demand typical of touristic areas add costs to these systems.
7. Due to the aforementioned touristic interest of these territories, environmental and fauna and flora protection requirements are stricter.

These features and the required fuel transportation make SEIE generation costs more expensive than the ones in the Peninsula. SEIE are operated under a centralized scheme. Resulting electricity tariff is compensated to guarantee equal tariffs in the whole Spanish system. Therefore, the demand is supplied by the cheapest generators and taking into account the expected demand and required security and quality levels. It is the System Operator (REE) the one developing the economic dispatch considering the variable costs of the generation plants. Red Eléctrica Española (REE) is also in charge of guaranteeing a secure, efficient and sustainable electricity supply by operating optimally the electric system and, as the Spanish TSO, by developing, investing and maintaining the transmission grid. In the islanded systems, REE is responsible for supervising in real time, programming of generation to cover the demand at minimum costs, procuring the equilibrium between generation and demand in real time and integrating safely as much renewable energies as possible. REE carries out the economic dispatch of the generation units and takes responsibility for the electrical measurement system in these islanded systems.

Therefore, the generation dispatch in these systems consists on a weekly, daily, intraday and real-time deviations planification that lead to a final production dispatch. To determine the economic dispatch, three dispatches will be defined: a first dispatch taking into account only economic criteria, a second dispatch considering both economic merit order and security requirements and, lastly, a third one including possible restrictions imposed by the transmission grid. In order to establish the generating groups, hydro (excluding run of the river) will be programmed first, aiming to economically optimize the system in the long term. Weekly, daily and in the intraday, the groups in each isolated system will be programmed. It is duty of Red Eléctrica Española (REE) to establish the generating units according to variable dispatch costs of the different groups and taking into account technical restrictions, necessary reserves to guarantee quality and security of supply and particularities of pumping hydro installations. REE is responsible for calculating the variable generating costs of the units and ancillary services costs, performing weekly, daily, intraday and final dispatch programmes in each system, calculating the availability of each power plant, guaranteeing demand supply in real time and the required ancillary services and reserves, solving technical constraints, calculating the final hourly price of generation, verifying the fulfilment of technical requirements to supply electricity and communicating to the CNMC (Comisión Nacional de los Mercados y la Competencia) the final energy liquidations, among others.

As stated in RD 738/2015, generators in non-peninsular systems are divided in two categories: category A includes hydro (excluding run of the river) and thermal generators and cogeneration power plants with net power greater than 15 MW, while category B refers to renewable energies and cogeneration power plants with a net power equal or lower than 15 MW. Generators that use renewable energies and, secondly, high efficiency cogeneration (both category A or B) have priority of dispatch in equal economic conditions, provided that system reliability and security of supply requirements are maintained.

Category A generators in these systems could be assigned a group of retributive technical and economical parameters as an additional remuneration to each installation of category A, depending on the technology and type of installation. These parameters will be established on each regulatory period and will remain constant for 6 years, until the beginning of the next regulatory period. Generators with this recognition have a variable generation cost composed of fuel variable costs, start-up costs, variable operation and maintenance costs, secondary reserve costs (remunerated in terms of availability as 1% of the dispatch variable operation costs), emission rights costs and reduction of variable costs due to incomes or avoided costs unrelated to electricity production. Other costs taken into account in this remuneration scheme are the access to transmission and distribution grids tolls, payments to the System Operator and taxes on electricity generation.

For generators in category A not being recognised the retributive parameters for additional remuneration it will be the owner of the facility the one communicating to the System Operator (REE) their variable costs for the dispatch.

Category B generators are remunerated according to their hourly selling price in the dispatch plus a payment for their contribution to ancillary services. Currently, this type of generators is assigned a variable cost of 10 €/MWh. This value could be modified by the Ministry of Industry, Energy and Tourism according to the variation of operation costs of these technologies. Moreover, an additional remuneration regime is established for Category B generators, as specified in the Royal Decree RD 413/2014 (Título IV). This additional remuneration is composed by a term per unit of installed power (€/MW) and a term related to the operation of the plant (€/MWh).

Regarding ancillary services, it is responsibility of the TSO to establish the level of reserves needed in each SEIE in order to make up for any kind of imbalance between generation and demand. In the same way as in the Iberian Peninsula, three levels of reserves are defined: primary, secondary and tertiary. Also, REE determines the maximum power being exchanged through the existing interconnections.

- Primary reserve. Each islanded system will have a primary reserve of at least 50% the net power of the biggest group committed for each hourly period. Each of the generators of a combined cycle power plant will be considered independently. Energy that could be supplied through interconnections to provide primary reserves will also be taken into account, using the N-1 criteria. Distributing this primary reserve between the different groups will be developed following the Primary reserve procedure.
- Secondary reserve. REE will establish the secondary reserve needs for each hourly period considering the predictable evolution of the demand, the probability of failure of committed generators and the wind power variability. When adding up both primary and secondary reserves

for each period, the total reserve must be higher than the higher net power between the committed generators in each period, the expected increase in demand between the analysed period and the following one, the power supplied from the interconnections with N-1 criteria and the most probable loss due to a decrease in wind power. Downward reserve in each period will be higher than 50% the upward reserve. Depending on the future evolution of the SEIE, these secondary reserve values could be modified. The total primary and secondary reserve is assigned according to economic criteria within the economic dispatch.

- Tertiary reserve. Upward tertiary reserves in each period will be at least equal to the biggest of the higher net power between the committed generators in each period, the expected increase in demand between the analysed period and the following one, the power supplied from the interconnections with N-1 criteria and the most probable loss due to a decrease in wind power. Again, these values may be modified according to future evolution of the SEIE.

Moreover, in order to verify an efficient operation of the systems, both the Government and the System Operator establish a maximum power to be remunerated in order to cover the demand, so no overcapacities are retributed. As previously mentioned, generators are committed considering their recognised variable costs, as determined by the System Operator, guaranteeing operation efficiency in the systems. Generators are audited annually to verify costs and functioning of the groups. Remuneration is, therefore, established according to standard values in normal conditions, evaluating generation costs per technology in the Iberian Peninsula and considering efficiency and particularities that can make the generation in these systems more expensive. These costs are reviewed in every regulatory period, which lasts 6 years. Finally, it is highlightable that a unique tariff is pursued and customers in the islands are offered the same tariffs as in any other territory of the Iberian Peninsula, socializing the difference in generation costs between the islands and the Iberian Peninsula among all consumers.

Lately, some modifications have been performed in the payment structure to generation. For example, it was approved that agents owning more than 40% of the installed power in the island would have limited permits for new installations. Also, reversible hydro plants should be owned by the System Operator when its objective is to guarantee security of supply, system security or non-manageable renewable generation integration. With respect to regasification plants, the owner should be the Technical Manager of the Gas System (Gestor Técnico del Sistema Gasista).

Moreover, some measures have been proposed and/or developed to help reducing generation costs in the islands: development natural gas pipelines and regasification plants to enable access to cheaper fuels in the islands, increase of renewable power plants projects, analysis of economic viability of possible interconnections between islanded systems and the continent or between islands, construction of pumping or reversible hydro generation plants and improvement of energy efficiency to optimize the consumption in the islands (distributed generation, smart metering, electric vehicles, batteries and smart grids).

All in all, it is the System Operator the one in charge of guaranteeing the viability of the system operation and establishing the procedure to supply the demand. If the respective mechanisms were already used, REE could take control of non-manageable generators in order to provide enough complementary services to guarantee voltage and frequency levels. The System Operator can also order the diminishment in the production of a power plant that is introducing extra energy that can not be handled in the system.

Lastly, particularizing in the system on which the analysis has been developed, the Canary Islands count with a high penetration of renewables, mainly wind energy. As common in this kind of systems, the grid is poorly meshed and generation groups are few and small, making stability and security of supply an issue. When generation is scarce (due to poor wind availability, failures or unavailabilities in the grid) storage gains importance and energy storage systems are been built: reversible hydroelectric plants. With these pumping systems, energy supply is guaranteed, together with system security and integration of not manageable renewables.

Moreover, new interconnections between islands are planned to improve the optimality in the operation of this system, as well as improvements in the network meshing.

As the Government promotes the increase of renewable energies integration, system stability, infrastructure quality, energy storage systems, interconnections and meshing of the network become even more important.

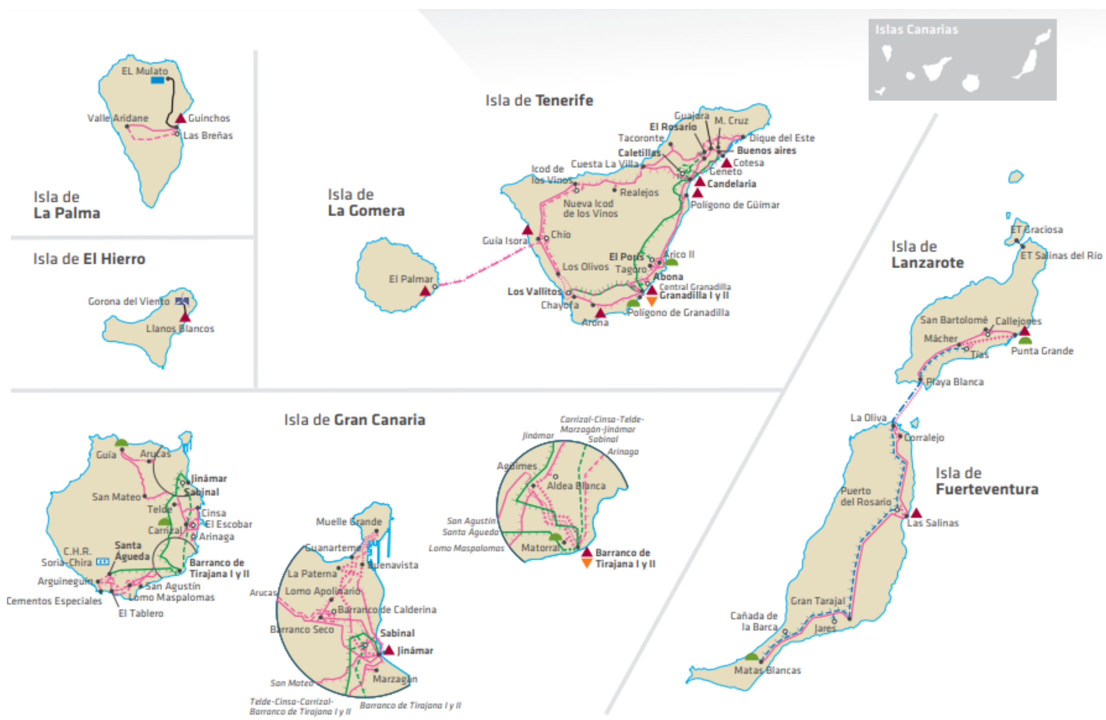

Figure 1: Planned and in-service transmission infrastructures in the Canary Islands. Source: REE.

1.3. Objectives

In this Master Thesis it is proposed to study the amount of spinning reserve that renewable energies could provide to increase the penetration of the same. To do this, a dispatch tool will be used that determines for each hour what generating groups are connected, how much they generate and how much reserve they provide. In addition, different scenarios of possible generation losses based on renewable energies (variation, loss of complete parks, etc.) must be generated and studied.

Therefore, different penetration scenarios of renewable energies that impact on technical criteria will be analysed, establishing as main objective the economic valuation of the service provided, as allowing renewable energies to provide spinning reserve will imply a variation of the generation from thermal plants and, therefore, it will have an economic impact in the dispatch.

Moreover, it will be determined in which situations renewable resources providing this ancillary service is profitable, establishing for example above which share of renewable energies it is beneficial for the system to let them participate in the spinning reserve. In relation to this, the appropriate reserve amount to be given by renewables will also be analysed.

Finally, it will be discussed if the existing reserve criteria is appropriate or not and whether the participation of renewable resources in spinning reserves is profitable for the system or not.

All in all, the different objectives of the project have one main goal: to determine the economic impact that renewable energies providing reserve has on the system, aiming to decrease the cost of the dispatch in isolated systems.

2. State of the art

Before developing this Master Thesis, the state of the art was analysed to determine if and at which extent the objectives of this project had been studied.

To contextualize, as stated in [1], ancillary services cover a range of products: frequency control, voltage control, spinning reserve, standing reserve, black start capability, remote automatic generation control, grid loss compensation and emergency control actions. Focusing on the topic of this project, it can be highlighted that reserve services are split into spinning reserve and standing or supplementary reserve. The spinning reserve is characterized by having a quick start capability, being fully available within 10 minutes, and it is used to cover unpredictable deficits, usually caused by outages of generators and tie-lines. On the other hand, standing reserve refers to those generators with a slower starting capability which are considered as backup for the spinning reserve. Taking up to 30 minutes to be brought online to the grid, it is used in special cases to meet additional contingencies.

Regarding the use of renewable energy sources as ancillary services, currently hydro and thermal plants are supplying these services, as the natural intermittency of wind power hinders its use to provide reserves. The article developed in Chalmers University of Technology [1] focuses on the use of wind power as voltage and frequency control by using variable speed wind turbines to modify the output power and power factor and therefore control reactive power, which is related with voltage, while frequency control can be achieved by either keeping the rotational speed of wind turbine at a higher or lower level than the optimal speed or changing the pitch angle of the wind turbine.

[2] studies the feasibility of wind and solar distributed generation providing ancillary services to medium-scale micro-grid, mainly as voltage support and stability services. Both the voltage and transient stability improve when adding the distributed generators to the system.

In [3], the importance of renewable generators providing ancillary services, such as frequency control, in energy systems with high RES penetration is highlighted and the economic impact of wind and PV generators participating in the German market providing negative secondary and tertiary control reserve is quantified. Thus, the article analyses the benefits of wind and solar energy supplying downward reserve and concludes that these generators are able to access the markets value in an increasingly competitive environment, although there is high dependency on the level of reliability, the product length and the auction lead-time. Also, the paper states that positive control reserve market segments are not analysed since fluctuating renewable generators are not competitive in the current market structure.

What is more [4], nowadays thermal plants need to provide higher reserves or be shut down in some periods as a consequence of an increase in the penetration of wind energy. This behaviour reduces the power plant lifetime and increases the costs. By using electronic converters in wind turbines, this kind of energies would be able to participate in the ancillary services, giving a flexible response in a short-time period. Providing negative (downward) reserves is relatively easy by changing the rotational speed or the pitch angle of the blades, although by reducing the output power of the wind turbine revenues are decreased. On the other hand, providing positive reserves means that the turbine can not be operated in its maximum power point, translated in a loss of revenue in normal operation. By this, it can be stated that there is no incentive for wind turbine operators to provide power reserves, unless financial compensation is ensured by the TSO. Even though currently it does not seem profitable for RES to provide positive reserves, the increasing levels of renewables will mean an increase of the short-term balancing costs that could make it economically viable in the future. With this paper, [4], a reference point for the output power of wind turbines is proposed in order to optimize the generation of this plants together with the minimum reserve that they are capable of supplying.

In [5], a stochastic approach is applied to deal with wind generation uncertainty. As offline approaches eliminate real-time computational issues of stochastic programming, an offline policy generation technique is proposed to provide a stochastic reserve margin to hedge against real-time uncertainty of wind farm generation. By this, it is expected that wind generators operate under their maximum output to hold some power as reserves. The article states that allowing wind generation to provide flexible reserve increases the stability in a system with increasing integration of large-scale wind generation.

[6] analyses with a two-stage optimization framework the implementation of a flexible dispatch margin to enable wind to participate in mitigating the variability and uncertainty of the system by under-scheduling in the hour-ahead market to have power margins available for the real-time market. The paper concludes that the higher the wind penetration, the higher the benefits from the flexible dispatch margin. With this proposal of flexible dispatch margin the dependency on thermal generators is decreased, together with the frequency of price spike events. Wind penetration is increased in a 20% (from 10% to 30%). Also, the article evaluates the effect of demand response together with flexible dispatch margin, proving that it can improve the power system performance.

While in [7] a methodology based on historical data and stochastic processes is studied to analyse the impact of wind on power system ancillary services including regulation and load following and it is proven to be effective, [8] states the importance of flexibility of generation or consumption in reserve markets as distributed RES increase its presence in the electric system. Again, demand-side response is put together with reserve markets to provide flexibility to hedge against uncertainty and some regulatory measures are proposed to enable distributed RES operators and demand response aggregators to be active in the markets.

[9] proposes a ramping coordinated control strategy for wind farms in order to provide to promote response speed, which would facilitate the provision of reserves. Wind farms are grouped into different joint power generation units, so a more reasonable scheduling plan is given. By this method, wind farms in each joint power generation unit coordinate to split the dispatching plan. As mentioned, to promote response speed a new kind of wind generation automatic generation control strategy is proposed, results showing that it enables wind generators to respond to the dispatching plan from power grid actively, guaranteeing the response of the wind farm to the scheduling plan. [17] also works on the idea of a flexible ramp product provided by wind power to respond to the varying load and intermittent generation. This would enable avoiding or at least reducing renewable generation curtailment due to the need of maintaining conventional plants connected to provide ramp capacity. Despite its uncertainty and variability, wind plants are proven to be capable of providing ramping capacity with reliable performance, especially in future scenarios of high wind penetration, as currently it may not be beneficial to allow renewable generators to provide this kind of products because of their low marginal costs. Co-optimizing energy, reserve and flexible ramp capacity products, results show that it is profitable for the system and, depending on the compensation scheme, also for wind plants to allow these generators to provide ramp capacity.

Articles [11] and [12] propose a linear reserve restriction for primary regulation, so it can be used with the mixed integer linear programming (MILP) used to solve the unit commitment (UC) problem. [11] studies the impact that these restrictions have in the UC by simulating the same system with and without reserve restrictions. The amount of primary reserve is determined by the frequency deviation and the droop of the generating group, both considered known. This paper only considers contingencies defined by the loss of prespecified combinations of generating units, which causes negative frequency deviations. [12] compares the results with real data from Taiwan, but it does not compare them with simulations without reserve restrictions. Results conclude that this method yields less cost of unit MW generation and frequency-regulating reserve schedules while the system security is maintained.

What is more, as per [13], the ERCOT system was evaluated to determine the impact of uncertainty in the inertia of the system and increase wind penetration by studying different economic dispatch models with different levels of spinning reserve. The ERCOT system is considered a large-scale isolated system and increasing levels of wind generation can cause higher frequency deviations due to the limited inertia and frequency control that this kind of generators provide. The paper proposes to incorporate minimum frequency constraints in a stochastic optimization framework in order to optimize the geographical allocation of reserves and the primary frequency control to minimize costs. Results obtained show that the stochastic economic dispatch model allocates energy and reserves schedule significantly reducing the expected operation costs in comparison with deterministic reserve requirements and it states that cost savings using this model are more significant under higher levels of wind integration.

In [14], wind uncertainty is considered in a stochastic Unit Commitment MILP formulation, concluding that synthetic inertia provided by wind turbines will have a strong influence on stability in scenarios with low conventional generators' participation.

[15] studies the case of isolated systems with increasing penetration of renewable sources, applied to the system of Lanzarote-Fuerteventura (Canary Islands, Spain) and the Crete System (Greece). As previously stated, higher amount of uncertain energy means a higher risk in this type of systems, as they are not interconnected and relay in a lower amount of backup power from conventional thermal plants. In this scenario, the paper proposes a stochastic Unit Commitment model that takes into account reserve requirements dependent on the forecasting horizon and the amount of renewable generation. Information regarding the UC cost and the risk mitigation is provided, allowing the system operator to make decisions measuring risk.

In [16] an assessment of the role and value of frequency response support from wind plants is developed, in order to enable wind turbines to provide synthetic inertia and primary frequency response. The article uses a stochastic unit commitment model and states that with an appropriately designed frequency controllers, wind plants could provide a fast frequency response similar to conventional plants. Different scenarios of wind penetration are studied in the Great Britain power system, as well as different degrees of required frequency response, concluding that it may be significantly beneficial for the system to allow wind plants to provide frequency response support and that synthetic inertia could effectively reduce the system operation cost. It is highlighted that the benefits are system specific.

In this line, [18] explains the different ways in which wind turbine output can be controlled to provide reserves, focusing on fixed-speed (type 1) and variable-slip (type 2) wind turbines, as with pitch control it is more complicated to control reserve power. Even though it is easier to implement spinning reserves with other types of wind turbines (type 3 and 4) because of the power converters, spinning reserve can be successfully implemented also when only having pitch controller. In high wind penetration scenarios, frequency support provided by wind turbines by these means is significant.

Moreover, importance of energy storage resources is highlighted in [19], as it provides flexibility as a solution to renewable energy sources variability.

Finally, as per February 2016, Acciona Energía was able to provide upward reserve with wind energy, increasing its production in more than 150 MW in a short-time period and becoming the first company in the world to provide ancillary services exclusively with this type of energy. [10]

3. Methodology

3.1. Description

As previously mentioned, in order to study the amount of spinning reserve that renewable energies could provide to increase the penetration of the same, a dispatch tool will be used that determines for each hour what generating groups are connected, how much they generate and how much reserve they provide.

Therefore, different scenarios of possible generation losses based on renewable energies (variation of power output, loss of complete power plants, etc.) will be generated in an already developed Matlab model, from which results will be obtained and will afterwards be analysed in depth. The study is developed in insular and extra-peninsular electric systems (SEIE for its acronym in Spanish). The generation assignment in these territories is not developed as a market but as an economic dispatch. Therefore, the model consists on a Unit Commitment (UC) developed in terms of power and seeking to minimize variable costs taking into account demand supply restrictions and other constraints, such as system security (reserves) and generators' technical restrictions (maximum and minimum output power, ramps, shut down and start up times, etc.).

Each scenario will be determined by a set of input data in Excel, which will be imported to the Matlab model. These data range from wind, solar and demand profiles to specifications regarding the value of upward and downward reserves, fixed and variable production costs and maximum and minimum power output for each technology, ramping and time up and down values for conventional generators, as well as the costs and number of hours to start up and shut down the plant. The model also allows to determine a binary variable that defines whether the output of wind and solar plants can be controlled and a cost penalization for conventional generators. Solution convergence can be limited by a tolerance gap between the solution being analysed and the previous one and by a solution time cap. The model is also prepared to receive input data regarding energy storage systems, demand side management and thermal demand, although no analysis is developed in this regard throughout the Master Thesis. From this Excel file, a coefficient defining the reserve to cover renewable energy losses can be highlighted. Its value will be set in a 10%, but a sensitivity analysis will be developed to determine the effects of having both a greater and a smaller coefficient.

The differences between scenarios will rely on the renewable generation profile and the amount of this generation that is allowed to provide reserve. This amount is determined by two parameters, both defined and modified in the Matlab code: the RES-to-reserve factor and the deload factor. The RES-to-reserve factor is a binary parameter that defines whether renewable resources are allowed to provide reserve ('1') or not ('0'), while the deload factor refers to the power that renewable generators stop producing (the difference between the real power output that could be produced and the actual value of power being produced) in order to be able to provide upward spinning reserve and it is applied only when renewable resources are allowed to provide reserve. Therefore, when the RES-to-reserve is one and the deload factor is equal to zero, no renewable energy is a priori reserved. However, since renewable generators could provide reserve, the UC decides whether and how much reserve will be finally provided. When the RES-to-reserve is one and the deload factor is greater than zero, at least as much renewable energy as specified in the deload factor is a priori reserved.

With this data, different scenarios of installed wind capacity will be analysed and, for each one, three cases will be studied:

1. RES not allowed to provide reserve (both RES-to-reserve and deload factors equal to zero)
2. RES allowed to provide reserve (RES-to-reserve equal to one, while deload factor remains null)
3. RES allowed to provide reserve deloading 10% of wind (RES-to-reserve equal to one and deload factor equal to 0.1)

Once the scenarios have been defined, the program is executed, obtaining the total cost of the dispatch and the power produced by each generator, including the energy spilled by renewable resources. The analysis carried out will consist mainly on the total cost obtained, justifying the cost variation with the way renewable energy sources are allowed (or not) to provide reserve and the power allocation between the different generators.

In summary, the methodology will consist on determining a series of scenarios to analyse, introducing them in the Matlab model, classifying the results and concluding their meaning regarding feasibility and economic impact.

3.2. Model

The model is developed in Matlab and mainly follows the one descripted in [25]. The only modifications consist in the introduction of new constraints related to RES providing reserve, as will be explained below. For the sake of ease of understanding, only those equations are presented relevant in the context of this Master thesis.

3.2.1. Parameters and variables

Therefore, the model is defined through a set of parameters, binary variables and continuous variables, abbreviated as:

- Sets:

g : thermal unit
h : hour

- Parameters:

C_g^{fix} : the fixed cost of unit g, [€]
C_g^{lin} : linear component of the variable cost of unit g, [€/MW]
C_g^{qua} : quadratic component of the variable cost of unit g, [€/MW^2]
$C_g^{start-up}$: start-up cost of generator g, [€]
$C_g^{shut-down}$: shut-down cost of unit g, [€]
$P_g^{\min}$: minimum power generation of unit g, [MW]
$P_g^{\max}$: maximum power generation of unit g, [MW]
R_g^{up} : ramp-up of unit g, [MW/h]
R_g^{down} : ramp-down of unit g, [MW/h]
D_h : total power demand in hour h, [MW]
$P_{wind,h}^{real}$: available wind power production of wind generation $wind$ in hour h, [MW]
$P_{wind}^{\min}$: minimum power generation of wind generation $wind$, [MW]
dld_{wind} : deloading factor of wind generation $wind$, [-]

- Binary variables:

$\delta_{g,h}$: state of unit g in hour h
$\delta_{g,h}$: state of wind generation $wind$ in hour h
$cx_{g,h}$: start-up decision of unit g in hour
$dx_{g,h}$: shut-down decision of unit g in hour h

- Continuous variables:

$p_{g,h}$: is the power generation of unit g in hour h, [MW]
$p_{wind,h}$: net wind power production in hour h, [MW]
$resso_h^{up}$: system operator ramp-up primary reserves required in hour h, [MW]
$resso_h^{down}$: system operator ramp-down primary reserves required in hour h, [MW]
$resgen_h^{up}$: ramp-up primary reserves provided by thermal generating units in hour h, [MW]
$resgen_h^{down}$: ramp-down primary reserves provided by thermal generating units in hour h, [MW]
$reswind_h^{up}$: ramp-up primary reserves provided by wind generation in hour h, [MW]
$reswind_h^{down}$: ramp-down primary reserves provided by wind generation in hour h, [MW]

3.2.2. Objective functions and constraints

The mathematical model used is composed of an objective function and different constraints.
As stated in [25], the objective is the minimization of the total thermal generation costs, yielding as output the start-up decisions of thermal units and hourly operation of both thermal and energy storage system units. The formulation of the objective function is:

$$\min \sum_{g,h} \Big[\Big(C_g^{fix} \cdot \delta_{g,h} + C_g^{lin} \cdot p_{g,h} + C_g^{qua} \cdot p_{g,h}^2 + \\ C_g^{start-up} \cdot cx_{g,h} + C_g^{shut-down} \cdot dx_{g,h} \Big) \Big]$$

where quadratic generator cost curves have been approximated by piecewise linear functions.

The different constraints applied are:

1. Demand balance:

   Concerning demand balance, equation (1) formulates that the total power generation (thermal units and wind) must be equal to total load demand.

$$\sum_g p_{g,h} + \sum_{wind} p_{wind,h} = D_h, \quad \forall h \tag{1}$$

2. Thermal technical operation:
   Concerning thermal technical operation, equation (2) imposes that thermal generation must be between maximum and minimum limits and equation (3) yields that thermal generation increase/decrease between two consecutive hours must fulfil generator ramp up and down limits.

$$P_g^{\min} \cdot \delta_{g,h} \le p_{g,h} \le P_g^{\max} \cdot \delta_{g,h}, \quad \forall g,h \tag{2}$$

$$-R_g^{down} \le p_{g,h+1} - p_{g,h} \le R_g^{up}, \quad \forall g,h \tag{3}$$

3. Wind power limits:

A priory wind power is limited by the available wind power. The upper limit is reduced if a deloading factor *dldwind* is imposed. However, wind power can only be varied if wind generation is controllable (receive set point variations), *ICwind.*

$$\begin{aligned} &P_{wind}^{\min} \cdot \delta_{wind,h} \le p_{wind,h} \le P_{wind}^{real} \cdot \left(1 - dld_{wind}\right) \cdot \delta_{wind,h} \quad \forall h, wind \in IC^{wind} \\ &P_{wind}^{\min} = P_{wind}^{real} \quad \forall h, wind \notin IC^{wind} \end{aligned} \tag{4}$$

4. System reserve:

Equations (5) and (6) compute the required upward and downward primary reserves by summing primary reserves of thermal and energy storage system units. As specified by isolated Spanish systems regulation, equations (7) and (8) force the up primary reserve to be greater than the largest connected unit and greater than the wind expected output. Also following Spanish regulation, equation (9) specifies that total down primary reserve must be greater than 50% of the up primary reserve.

$$resso_h^{up} = resgen_h^{up} + reswind_h^{up}, \quad \forall h \tag{5}$$

$$resos_h^{down} = resgen_h^{down} + reswind_h^{down}, \quad \forall h \tag{6}$$

$$resso_h^{up} \ge p_{g,h}, \quad \forall g,h \tag{7}$$

$$resso_h^{up} \ge k_{wind} \cdot P_{wind,h}^{real}, \quad \forall h, wind \tag{8}$$

$$resso_h^{down} \ge k_{down2up} \cdot resso_h^{up}, \quad \forall h \tag{9}$$

5. Reserve provided by generator units:

Computation of upward and downward primary reserves provided by thermal units are formulated in equations (10) and (11).

$$resgen_h^{down} = \sum_g \left(p_{g,h} - P_{g,h}^{\min} \cdot \delta_{g,h} \right), \quad \forall h \tag{10}$$

$$resgen_h^{up} = \sum_g \left(P_{g,h}^{\max} \cdot \delta_{g,h} - p_{g,h} \right), \quad \forall h \tag{11}$$

6. Reserve provided by wind generation:

Wind generation can provide up and down reserves. Up reserves can be provided if final generation set point is below the available wind power. Up reserve can only be provided by wind generation if they participate in the spinning reserves (*RES-to-reserve*)

$$\begin{aligned} reswind_h^{up} &= \sum_{wind \in RES-to-reserve} P_{wind,h}^{real} \cdot \delta_{wind,h} - p_{wind,h} \\ reswind_h^{down} &= \sum_{wind \in RES-to-reserve} p_{wind,h} - P_{wind}^{\min} \cdot \delta_{wind,h} \end{aligned} \tag{12}$$

4. Case studies

4.1. Description

4.1.1. La Palma

In order to optimize the dispatch, information regarding conventional generators in the island is needed. Technical data of these generators for the island of La Palma is shown in Table 1: maximum power, minimum power, ramp up, rump down, number of hours to shut down (nhsd), number of hours to start up (nhsu), number of hours down and number of hours up. On the other hand, Table 2 reflects the different costs derived from the operation of the generator: fix costs, linear costs, quadratic costs, shut down and start-up costs. No conversion from heat to power nor any kind of penalization to thermal generators has been considered.

	$P_{g_{max}}\ (kW)$	$P_{g_{min}}\ (kW)$	$r_{up}\ (kW/h)$	$r_{down}\ (kW/h)$	$nhsd$	$nhsu$	$nhtd$	$nhtu$
LGCHD06	3,8	2,4	3,82	-3,82	1	1	1	1
LGCHD07	3,8	2,4	3,82	-3,82	1	1	1	1
LGCHD08	3,8	2,4	3,82	-3,82	1	1	1	1
LGCHD09	4,3	2,82	4,30	-4,30	1	1	1	1
LGCHD10	6,7	3,3	6,70	-6,70	1	1	1	1
LGCHD11	6,7	3,3	6,70	-6,70	1	1	1	1
LGCHD12	11,5	6,63	11,50	-11,50	1	1	1	1
LGCHD13	11,2	6,63	11,20	-11,20	1	1	1	1
LGCHD14	11,5	6,63	11,50	-11,50	1	1	1	1
LGCHD15	11,5	6,63	11,50	-11,50	1	1	1	1
LGCHGM2	21	4,85	21,00	-21,00	1	1	1	1

Table 1: Conventional generators' technical data (La Palma)

	c_{fix} (€)	c_{lin} (€$/kWh$)	c_{quad} (€$/kWh^2$)	c_{sd} (€)	c_{su} (€)
LGCHD06	53,0	80,7	0,849	0,0	100,0
LGCHD07	53,0	80,7	0,849	0,0	100,0
LGCHD08	53,0	80,7	0,849	0,0	100,0
LGCHD09	89,9	86,4	0,633	0,0	100,0
LGCHD10	134,9	80,6	0,383	0,0	100,0
LGCHD11	134,9	80,6	0,383	0,0	100,0
LGCHD12	120,7	73,2	0,339	0,0	100,0
LGCHD13	125,9	90,2	0,220	0,0	100,0
LGCHD14	125,9	90,2	0,220	0,0	100,0
LGCHD15	125,9	90,2	0,220	0,0	100,0
LGCHGM2	636,3	110,7	0,082	0,0	100,0

Table 2: Conventional generators' economic data (La Palma)

Regarding renewable sources, PV and wind generation in La Palma throughout a week (168 hours) is shown in Figure 2 and Figure 3.

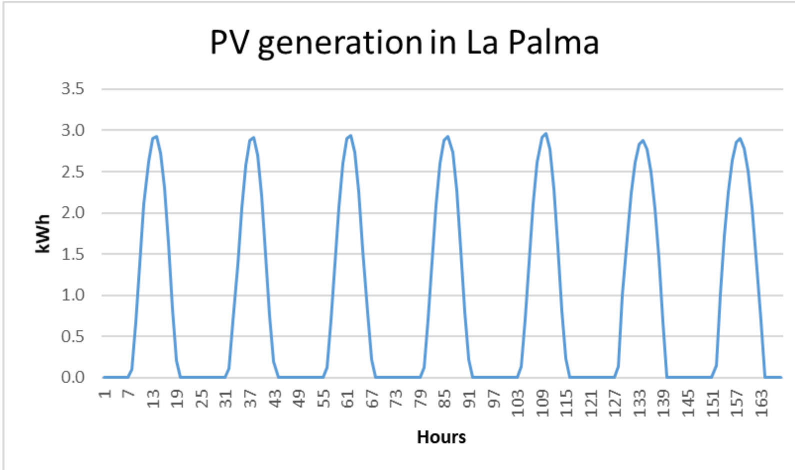

Figure 2: Current PV generation profile in La Palma

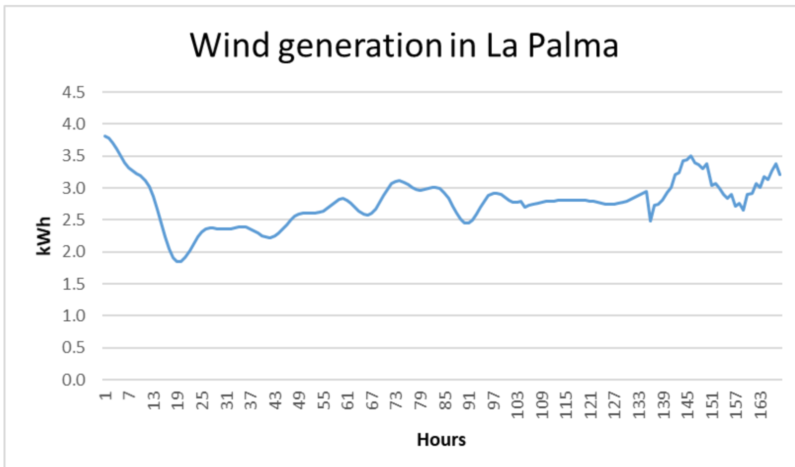

Figure 3: Current wind generation profile in La Palma

Finally, Figure 4 shows electricity demand data for one week:

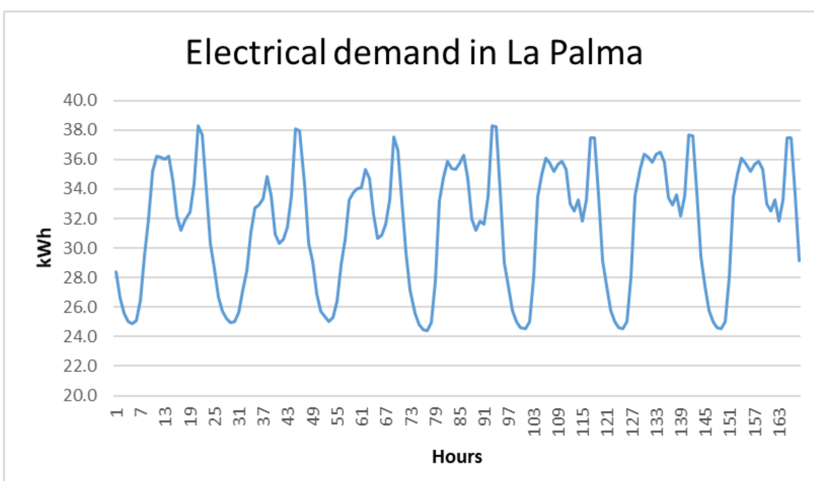

Figure 4: Demand profile in La Palma

In the following analysis, no energy storage systems, heat to power conversion nor demand side management have been considered.

4.1.2. Gran Canaria

Analogously to the case of La Palma, technical data of conventional generators in Gran Canaria is shown in Table 3, while the different costs derived from the operation of these generators are shown in Table 4.

	$P_{g_{max}}$ (kW)	$P_{g_{min}}$ (kW)	r_{up} (kW/h)	r_{down} (kW/h)	$nhsd$	$nhsu$	$nhtd$	$nhtu$
JINAD01	8.5	4.6	8.5	-8.5	1	1	1	1
JINAD02	8.5	4.6	8.5	-8.5	1	1	1	1
JINAD03	8.5	4.6	8.5	-8.5	1	1	1	1
JINAD04	19.1	14.8	20.5	-20.5	1	1	1	1
JINAD05	19.1	14.8	20.5	-20.5	1	1	1	1
JINAG01	17.6	6.8	17.6	-17.6	1	1	1	1
JINAG02	32.3	6.8	32.3	-32.3	1	1	1	1
JINAG03	32.3	6.8	32.3	-32.3	1	1	1	1
JINAV04	55.6	19.7	55.6	-55.6	1	1	1	1
JINAV05	55.6	19.7	55.6	-55.6	1	1	1	1
BRRCG01	32.3	6.8	32.3	-32.3	1	1	1	1
BRRCG02	32.3	6.8	32.3	-32.3	1	1	1	1
BRCCCC1_G3	68.7	9.7	68.7	-68.7	1	1	1	1
BRCCCC1_G4	68.7	9.7	68.7	-68.7	1	1	1	1
BRCCCC1_G3V	93.1	43.9	103	-103	1	1	1	1
BRCCCC1_G4V	93.1	43.9	103	-103	1	1	1	1
BRCCCC1_G3G4V	186	75.5	206.1	-206.1	1	1	1	1
BRRCV01	74.2	29.3	74.2	-74.2	1	1	1	1
BRRCV02	74.2	29.3	74.2	-74.2	1	1	1	1
BRCCCC2_G5	75.0	9.7	75.00	-75.00	1	1	1	1
BRCCCC2_G6	75.0	9.7	75.00	-75.00	1	1	1	1
BRCCCC2_G5V	113.5	43.9	113.50	-113.50	1	1	1	1
BRCCCC2_G6V	113.5	43.9	113.50	-113.50	1	1	1	1
BRCCCC2_G5G6V	189	89.5	227.00	-227.00	1	1	1	1

Table 3: Conventional generators' technical data (Gran Canaria)

	c_{fix} (€)	c_{lin} $(€/kWh)$	c_{quad} $(€/kWh^2)$	c_{sd} (€)	c_{su} (€)
JINAD01	108	87	0.212	0.0	100.0
JINAD02	108	87	0.212	0.0	100.0
JINAD03	108	87	0.212	0.0	100.0
JINAD04	364	48	0.528	0.0	100.0
JINAD05	364	48	0.528	0.0	100.0
JINAG01	1434	140	0.325	0.0	100.0
JINAG02	1744	114	0.069	0.0	100.0

JINAG03	1744	114	0.069	0.0	100.0
JINAV04	571	92	0.007	0.0	100.0
JINAV05	571	92	0.007	0.0	100.0
BRRCG01	1744	114	0.069	0.0	100.0
BRRCG02	1744	114	0.069	0.0	100.0
BRCCCC1_G3	3961	98	0.027	0.0	100.0
BRCCCC1_G4	3961	98	0.027	0.0	100.0
BRCCCC1_G3V	8284	-20	0.575	0.0	100.0
BRCCCC1_G4V	8284	-20	0.575	0.0	100.0
BRCCCC1_G3G4V	14536	-23	0.296	0.0	100.0
BRRCV01	878	75	0.008	0.0	100.0
BRRCV02	878	75	0.008	0.0	100.0
BRCCCC2_G5	3961	98	0.027	0.0	100.0
BRCCCC2_G6	3961	98	0.027	0.0	100.0
BRCCCC2_G5V	8284	-20	0.575	0.0	100.0
BRCCCC2_G6V	8284	-20	0.575	0.0	100.0
BRCCCC2_G5G6V	14536	-23	0.296	0.0	100.0

Table 4: Conventional generators' economic data (Gran Canaria)

Regarding renewable sources, PV and wind generation in Gran Canaria throughout a week (168 hours) is shown in Figure 5 and Figure 6.

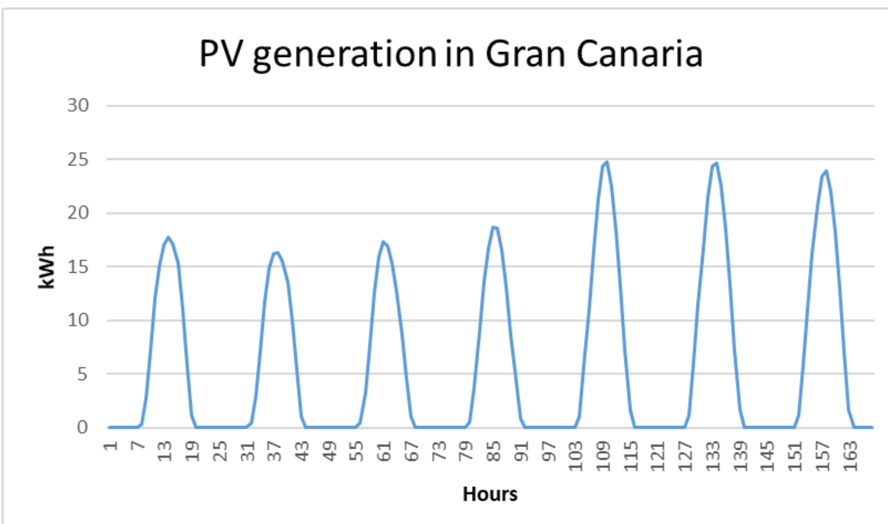

Figure 5: Current PV generation profile in Gran Canaria

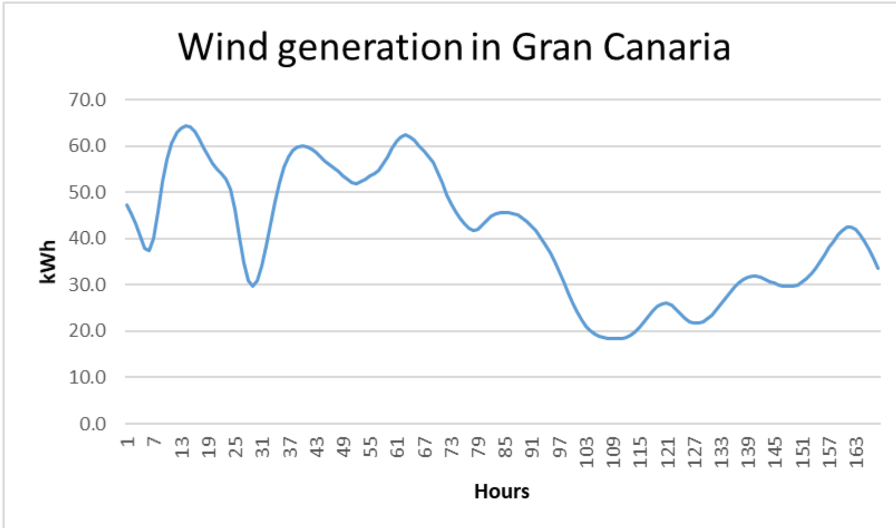

Figure 6: Current wind generation profile in Gran Canaria

Finally, Figure 7 shows electricity demand data for one week:

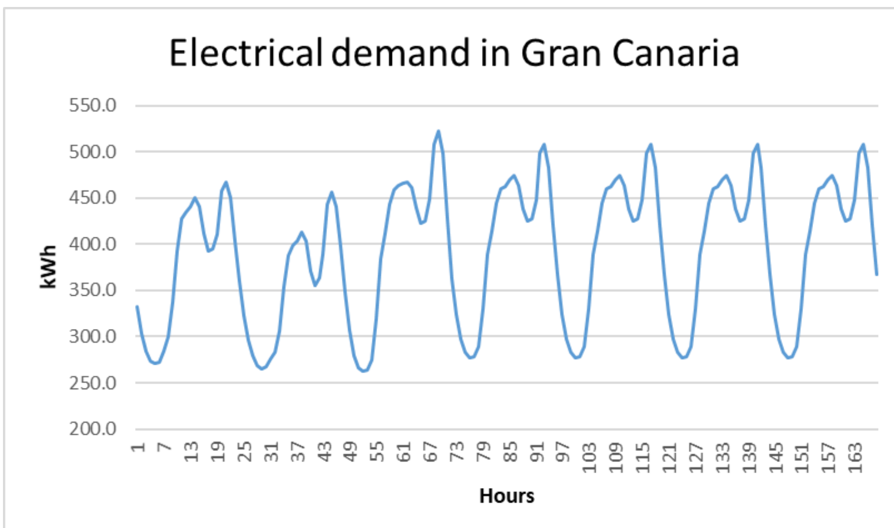

Figure 7: Demand profile in Gran Canaria

In the following analysis, no energy storage systems, heat to power conversion nor demand side management have been considered.

4.2. Scenario definitions

4.2.1. Actual and future RES capacity

The study has been developed independently in the islands of La Palma and Gran Canaria, belonging to the Canary Islands archipelago. Renewable energies penetration is greater in this archipelago than in the Balearic Islands, Ceuta or Melilla and the analysis of the two islands, with different sizes and generation scenarios, enables to reach more solid conclusions.

Figure 8 and Figure 9 show current demand and supply data in La Palma and Gran Canaria according to *Red Eléctrica Española* (REE).

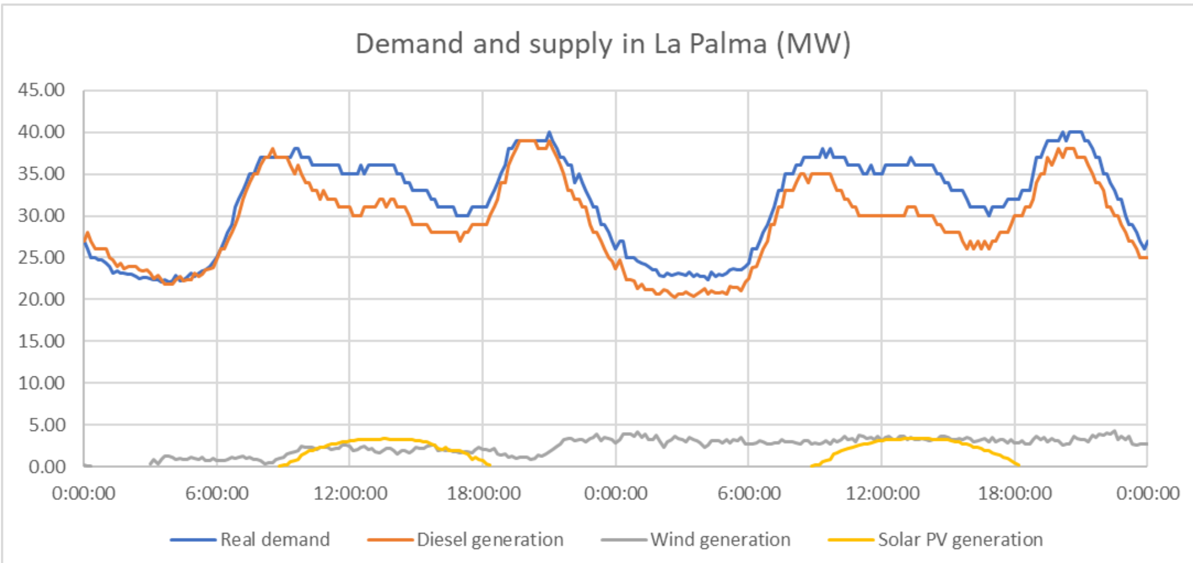

Figure 8: Demand and supply in La Palma, for February 6th and 7th, 2019. Source: REE.

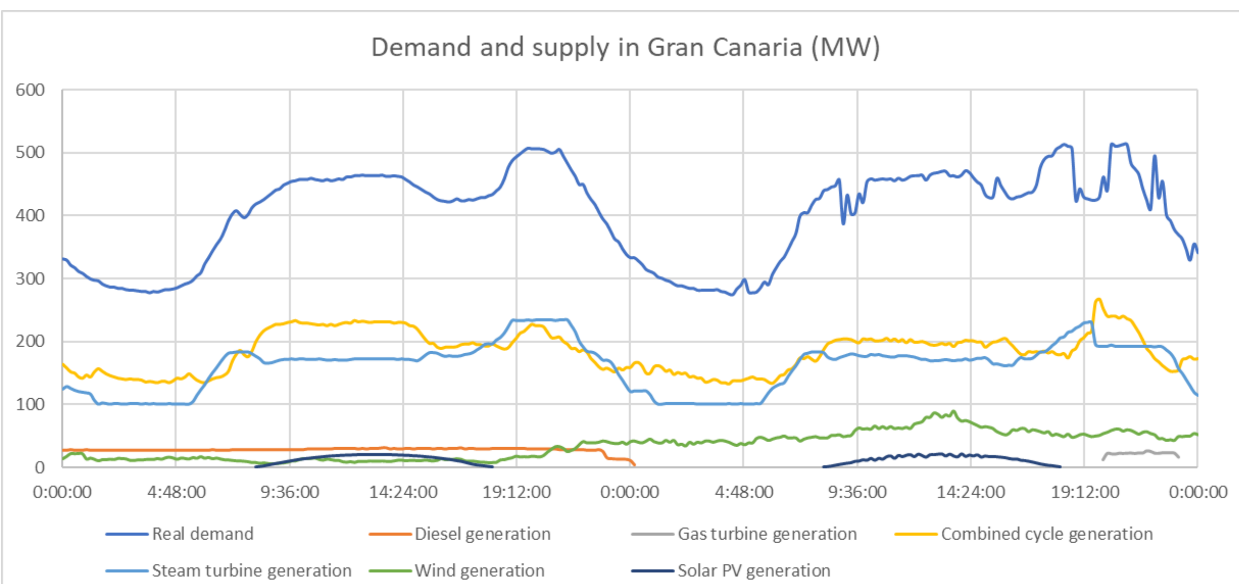

Figure 9: Demand and supply in Gran Canaria, for February 6th and 7th, 2019. Source: REE.

According to data from the Canary Government [21], in 2016, La Palma had an installed capacity of 105.3 MW in thermal plants, 7 MW in wind energy, 4.6 MW in solar PV and 0.8 MW in small hydro, summing up to 117.7 MW of installed power in the whole island. Moreover, La Palma counts with 38.07 kW of isolated solar PV. Therefore, considering wind, solar and hydro power connected to the grid, renewable sources account for around 10.5% of the installed capacity in La Palma. What is more, according to Figure 8, it can be observed that RES have a huge margin to grow in La Palma system, since nowadays almost all the demand is supplied with conventional generators. In the case of Gran Canaria, the installed capacity in 2016 was of 999.2 MW in thermal plants, 24.9 MW of cogeneration, 88.1 MW in wind energy and 40 MW in solar PV. The total amount of installed power in the island of Gran Canaria is 1,152.2 MW. Isolated solar PV in Gran Canaria accounts for 124.12 MW. All in all, 11.1% of the installed capacity in Gran Canaria is renewable.

This decomposition of RES sources is shown in Figure 10, while Figure 11 reflects the energy produced in 2016 with renewable generation in the islands.

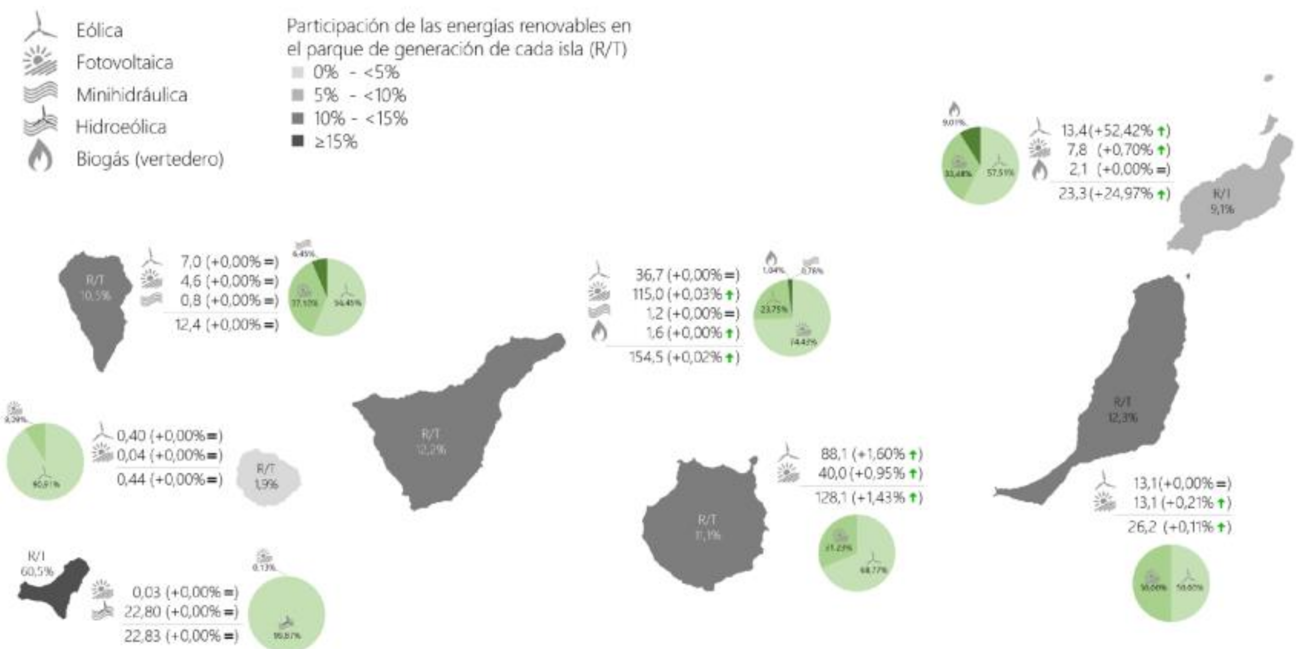

Figure 10: Renewable sources installed power (MW) in the Canary Islands (December 2016). Source: Anuario Energético de Canarias 2016 [21]

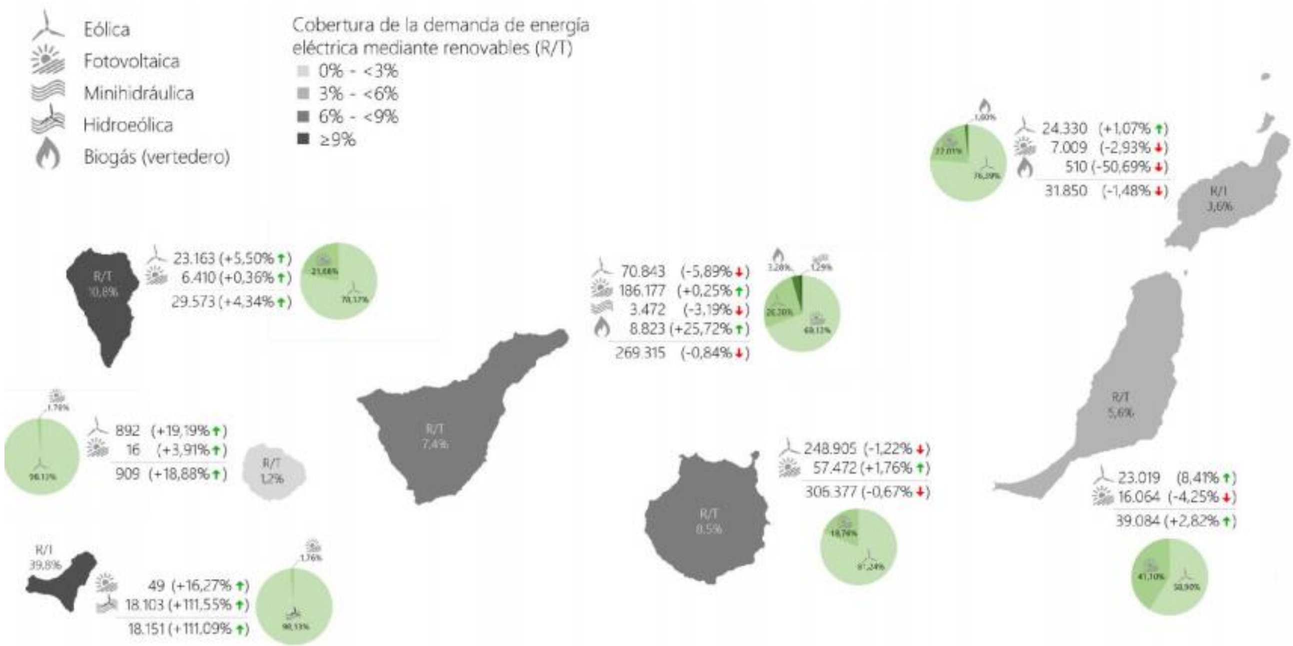

Figure 11: Energy produced (MWh) by renewable sources in the Canary Islands (2016). Source: Anuario Energético de Canarias 2016 [21]

Following this line, Figure 12 summarizes the generation sources (in percentage, %) of the different islands, having La Palma and Gran Canaria a similar percentage of RES than the rest of the islands. El Hierro excels with a 60.5% of installed renewable.

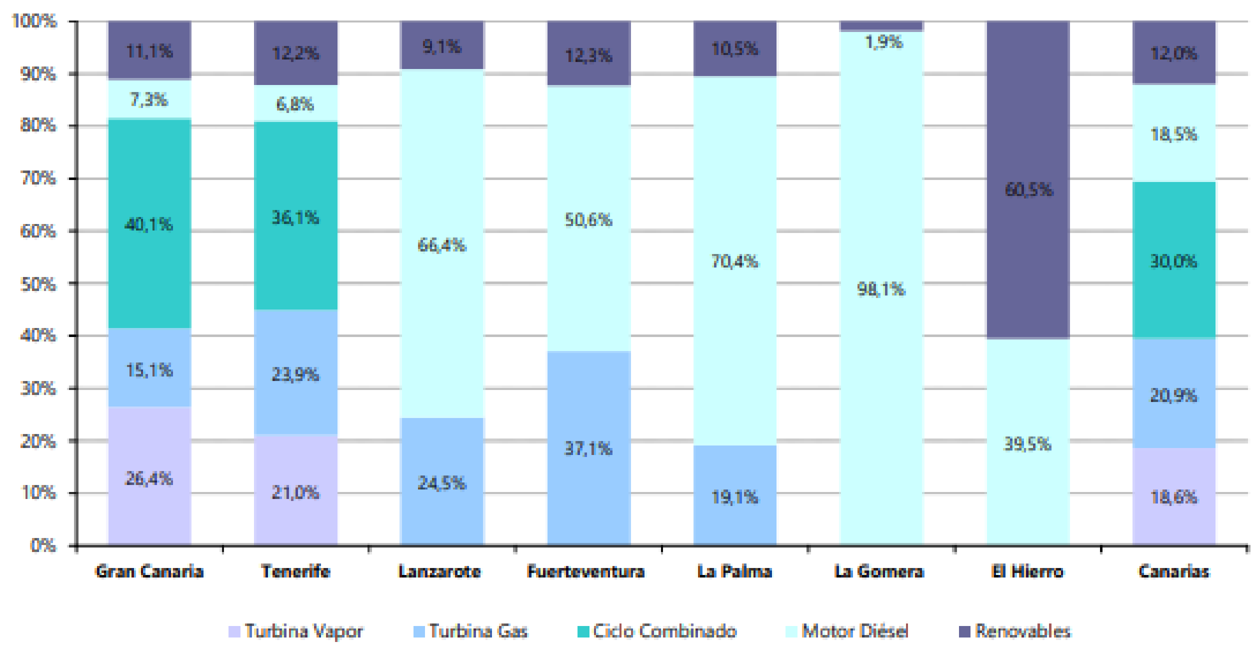

Figure 12: Technological structure of the generation plants in the Canary Islands (2016). Source: Anuario Energético de Canarias 2016 [21]

Regarding energy injected to the grid, Table 5 shows the percentage of renewable energy injected to the system per month. Focusing on La Palma, between 6.4% and 18.5% of the energy supplied to the grid comes from renewable sources, while the range in Gran Canaria was between 3.7% and 14.8%. Again, it can be observed that El Hierro has the highest percentage of renewable energy supplied to the grid.

Mes	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canarias
Enero	5,4%	6,7%	3,3%	2,7%	8,1%	1,0%	22,2%	5,6%
Febrero	11,2%	8,3%	5,0%	6,0%	16,5%	1,7%	53,4%	9,4%
Marzo	9,1%	8,4%	4,7%	6,5%	12,2%	1,4%	40,6%	8,4%
Abril	8,3%	7,4%	4,4%	7,3%	9,9%	1,3%	36,9%	7,6%
Mayo	9,0%	7,9%	5,3%	8,1%	12,4%	1,6%	25,6%	8,3%
Junio	13,2%	9,4%	5,9%	9,2%	15,5%	2,1%	53,7%	10,9%
Julio	14,8%	9,7%	5,8%	9,7%	18,5%	1,8%	66,1%	11,8%
Agosto	12,2%	9,0%	4,7%	7,0%	15,6%	1,6%	53,5%	10,0%
Septiembre	12,4%	9,1%	4,2%	6,6%	15,9%	1,6%	56,6%	10,1%
Octubre	4,3%	5,6%	2,3%	3,1%	6,4%	0,3%	19,8%	4,6%
Noviembre	4,6%	5,8%	3,2%	3,0%	9,7%	0,7%	29,2%	5,1%
Diciembre	3,7%	5,1%	3,3%	3,9%	7,9%	0,5%	27,2%	4,5%

Table 5: Percentage of renewable energy regarding the energy injected to the grid each month (2016). Source: Anuario Energético de Canarias 2016 [21]

With this generation mix and according to the 2015-2025 Canary Energetic Strategy [22], average annual price in 2015 was 160 €/MWh, decreasing a 20.2% in comparison with 2014's values. Maximum monthly price was 176.18 €/MWh in 2015, in contrast with the maximum monthly price registered in the 2011-2015, which reached 231.65 €/MWh in December of 2012.

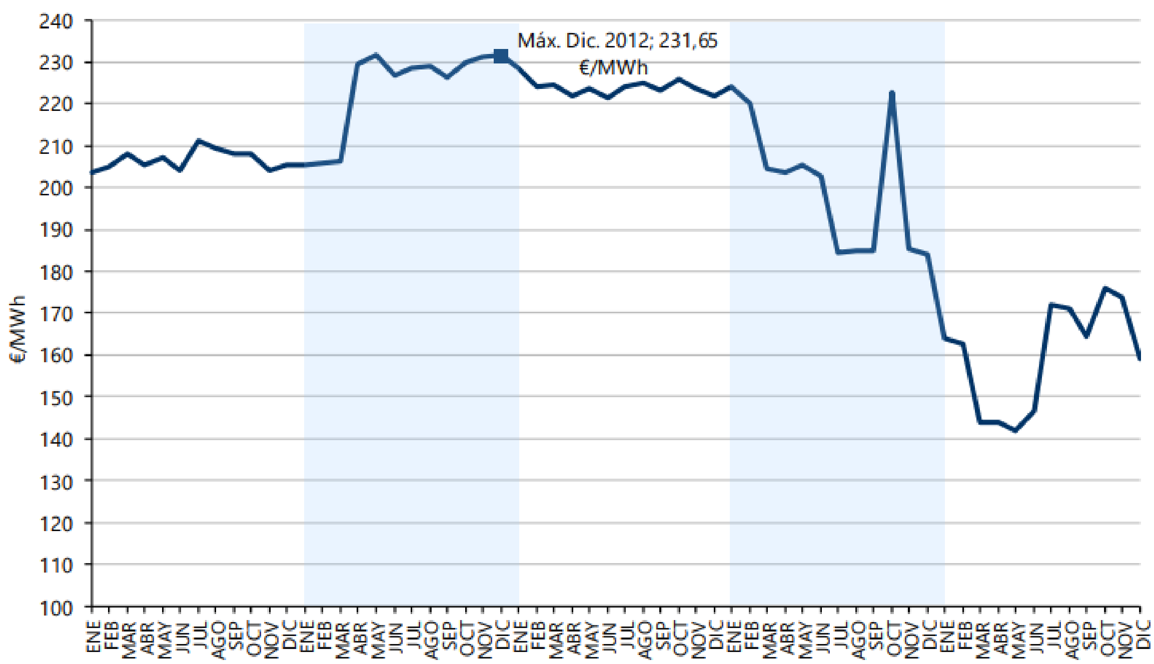

Figure 13: 2011-2015 electricity generation average monthly prices. Source: Estrategia Energética de Canarias 2015-2025 [22]

Focusing on future evolution of the sector, the Energy Strategy for the Canary Islands between 2015 and 2025 expects, as a moderate scenario, wind energy to reach 673 MW if the Transport Grid Development Plan 2015-2020 (Plan de Desarrollo de la Red de Transporte 2015-2020) is followed. Pumped hydro storage plants are also taken into account, considering the wind-hydro power plant already operating in El Hierro (Gorona del Viento – 11.5 MW) and the hydro plant in administrative processing in Gran Canaria (Chira Soria – 200 MW). Moreover, new interconnections are planned between islands: reinforcing of Lanzarote-Fuerteventura connection and the development of the interconnection between La Gomera and Tenerife. More optimistic scenarios also consider the construction of offshore wind farms (310 MW), biomass (25.5 MW) and photovoltaic energy (up to 300 MW), together with the previously mentioned pumped hydro power plants plus additional power hydro plants in Tenerife (90 MW) and La Palma (30 MW).

The Energy Strategy for the Canary Islands in 2025 aims to drive the system to a low carbon economy, proposing a group of basic principles, among which the following are included:

- Guarantee security of supply through the diversification of energy sources
- Reach the maximum renewable energy penetration, mainly wind and solar energy, while boosting also energies such as biomass, low temperature geothermal or waste energy use.
- Mitigate the vulnerabilities that the archipelago has due to its islanded condition and the remoteness of the islands from the European continent by reinforcing the transport and distribution grids and installing energy storage infrastructures.

Strategic objectives for the 2015-2025 period regarding renewable energies involve achieving a 15% of RES participation in final energy consumption by 2025 (in 2015 RES participation was of 2%), increase the generation of electricity by renewable sources up to 45% by 2025 (RES generation was 8% of the total electricity generation in 2015) and reducing CO_2 emissions on a 21% by 2025 with respect to 2014. Focusing on electricity generation, apart from the 45% objective of RES electricity generation by 2025, natural gas is proposed as an alternative fuel for the energy transition between the current model based on fuel and the new one with renewable energies, setting as an objective that in 2025 22% of the electricity is generated with this fuel while other fuels are reduced from 92% to 33% of energy production.

Regarding specifically renewable energies, the Canary Islands' Energy Strategy 2015-2025 contemplates an increase in installed power, installing 861 MW between 2015 and 2025. Also, a goal of 310 MW offshore wind power is set, together with the increase in solar energy participation in electricity generation, aiming to install 120 MW of solar power on this period. Biogas is also favoured in electricity generation, with an objective of 25 MW of installed power by 2025, while in 2015 the installed power was of 4 MW.

In order to achieve these objectives, energy infrastructures are promoted, with projects like the installation of three pumped hydro power plants in Gran Canaria, Tenerife and La Palma, reaching up to 332 MW when taking into account the already operating plant in El Hierro. Regasification plants are also contemplated in the islands, to enable the provisioning of cheaper natural gas for electricity generation. Lastly, reinforcing and construction of new interconnections between islands is fostered, transforming the 6 electrical isolated systems into 4 by connecting Tenerife and La Gomera as a single system and Gran Canaria, Fuerteventura and Lanzarote as another one.

All in all, implementation of large-scale renewables (mainly wind and solar) in the islands is a huge challenge, taking into account its decentralization and intermittency characteristics. Low predictability of these energies is a big issue in small scale islanded systems, in which enough conventional generators have to always remain connected to guarantee security of supply and energy storage systems, interconnections between islands and demand management measures become necessary if RES penetration wants to be increased. In addition, the aforementioned characteristics of the Spanish archipelagos interpose more difficulties, as shortage of land makes it very competitive (if possible) to get permits for its implementation, reason why off-shore wind would be a good solution in these islands. Despite these inconvenients, renewable energies in the islands open the door to an increase in energy supply, reducing both greenhouse gas emissions and dependency on imported fuel products. Moreover, high costs of thermal generation in the islands make it more profitable to install renewable energies, providing justification to the priority that this kind of energies have on the economic dispatch of the islands, establishing specific participation quotas of RES in the system.

Definitely, the Canary Islands' commitment to renewable energies is clearly reflected in Figure 14, in which objectives of installed renewable power for 2025 are shown, disaggregated by islands and technologies.

Tecnología	Capacidad instalada de origen renovable para la generación eléctrica con vertido a red, por islas (MW)													
	Gran Canaria		Lanzarote		Fuerteventura		Tenerife		La Palma		La Gomera		El Hierro	
	2015	2025	2015	2025	2015	2025	2015	2025	2015	2025	2015	2025	2015	2025
Eólica	86,72	408,50	8,78	81,00	13,09	87,00	36,68	412,00	6,97	21,00	0,36	4,00	11,50	11,50
Eólica off shore	0,00	180,00	0,00	10,00	0,00	10,00	0,00	100,00	0,00	10,00	0,00	0,00	0,00	0,00
Fotovoltaica	39,59	65,62	7,77	13,12	13,05	21,82	114,93	191,60	4,60	7,72	0,04	0,06	0,03	0,08
Biomasa eléct.	0,00	10,00	2,10	2,50	0,00	1,50	1,60	10,00	0,00	0,50	0,00	0,50	0,00	0,50
Total isla	126,31	664,12	18,65	106,62	26,14	120,32	153,21	713,6	11,57	39,22	0,4	4,56	11,53	12,08

Figure 14: Installed renewable power objectives for 2025 by islands and technologies. Source: Anuario Energético de Canarias 2016 [21]

4.2.2. Scenarios

As previously explained different scenarios of installed wind capacity have been analysed, being:

- Scenario 1: Current scenario
- Scenario 2: Scenario with twice the current installed wind capacity
- Scenario 3: Scenario with five times the current installed wind capacity
- Scenario 4: Scenario with ten times the current installed wind capacity
- Scenario 5: Scenario with fifteen times the current installed wind capacity
- Scenario 6: Scenario with twenty times the current installed wind capacity

For each one of these scenarios, three cases have been studied:

A. RES not allowed to provide reserve (both RES-to-reserve and deload factors equal to zero)
B. RES allowed to provide reserve (RES-to-reserve equal to one, while deload factor remains null)
C. RES allowed to provide reserve deloading 10% of wind (RES-to-reserve equal to one and deload factor equal to 0.1)

In the simulations, an upward reserve covering the loss of the biggest generation unit and 10% of the renewable generation has been considered. Simulations have been developed for a time scope of one day (24 hours) and throughout a whole week. A tolerance gap of 1% or a solution time of $300s$ has been set as convergence criteria. It must be taken into account that the tolerance is not the same for all the simulations, so real results might differ from the ones shown.

Moreover, wind and solar energy intermittency modifies the output that these sources can supply in real time. For this reason, a parameter has been used to determine the expected RES loss that reserves have to be able to cover.

With this purpose, a sensitivity analysis has been performed, simulating three additional cases, applied to Scenario 6 in La Palma and Scenario 3 in Gran Canaria, have been analysed:

- Scenario x.1: RES loss coefficient of 5% the renewable generation. Scenario with twenty times the current installed wind and a RES loss coefficient of 0.05 considered for the reserves.
- Scenario x.2: RES loss coefficient of 10% the renewable generation. Scenario with twenty times the current installed wind and a RES loss coefficient of 0.1 (10%) considered for the reserves
- Scenario x.3: RES loss coefficient of 20% the renewable generation. Scenario with twenty times the current installed wind and a RES loss coefficient of 0.2 (20%) considered for the reserves

4.3. Results

4.3.1. La Palma

With these settings, Table 6 summarizes the total cost of the daily dispatch obtained for the three cases and six scenarios analysed in the island of La Palma.

	Case A	**Case B**	**Case C**
Scenario 1	71,569	69,347	69,739
Scenario 2	64,324	63,220	63,825
Scenario 3	53,938	45,187	46,622
Scenario 4	49,134	17,850	19,557
Scenario 5	47,554	5,035	6,131
Scenario 6	47,216	595	968

Table 6: Total cost of dispatch in La Palma (€)

A more detailed decomposition of the numerical results is shown in **Annex: Numerical results**.

It can be highlighted that, as shown in Table 6 and for any of the scenarios studied, the optimal dispatch that minimizes the cost is obtained when RES are allowed to provide reserve without deloading wind. Figure 15 graphically reflects this behaviour: the higher the wind installed power, the cheapest the dispatch is and, for each and all the cases, total costs are lower when allowing wind power plants to provide reserves without deloading any percentage of wind. Even though costs are reduced between consecutive scenarios for all the scenarios, it is highlightable the huge reduction displayed between scenarios 3 and 4.

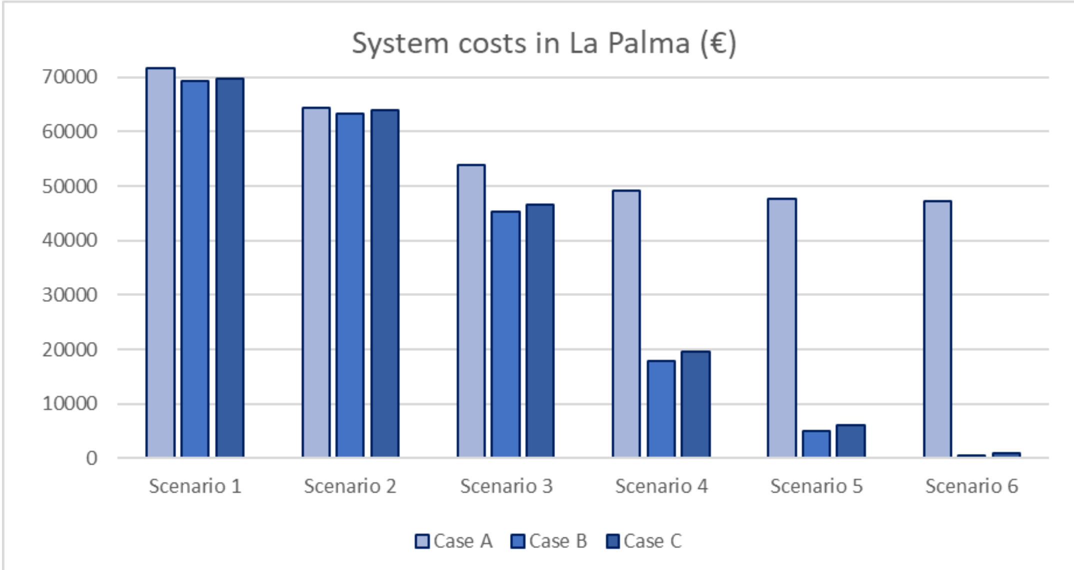

Figure 15: Total dispatch costs in La Palma (€)

When comparing the costs in each case and scenario with the current scenario without allowing wind power to provide ancillary services, a percentage of system cost reduction in the island is obtained (Figure 16). Again, it is remarkable that the biggest step is produced between scenario 3 and 4. System costs keep decreasing in the subsequent scenarios, although the evolution is not as noticeable as between 3 and 4.

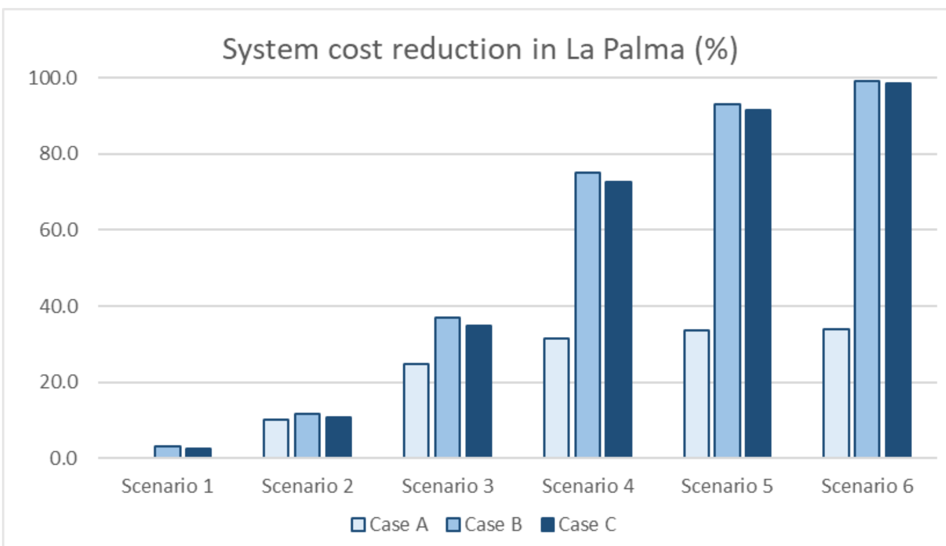

Figure 16: System cost reduction in La Palma (compared to current scenario and Case A)

The observed details are also reflected in Figure 17, where a comparison between each scenario with the directly previous one for each case (A, B and C). It seems clear that allowing wind power to provide reserve brings huge cost reductions to the system. Moreover, not deloading any amount of wind leads to the optimal solution, even though differences with Case C are slight compared with differences with Case A.

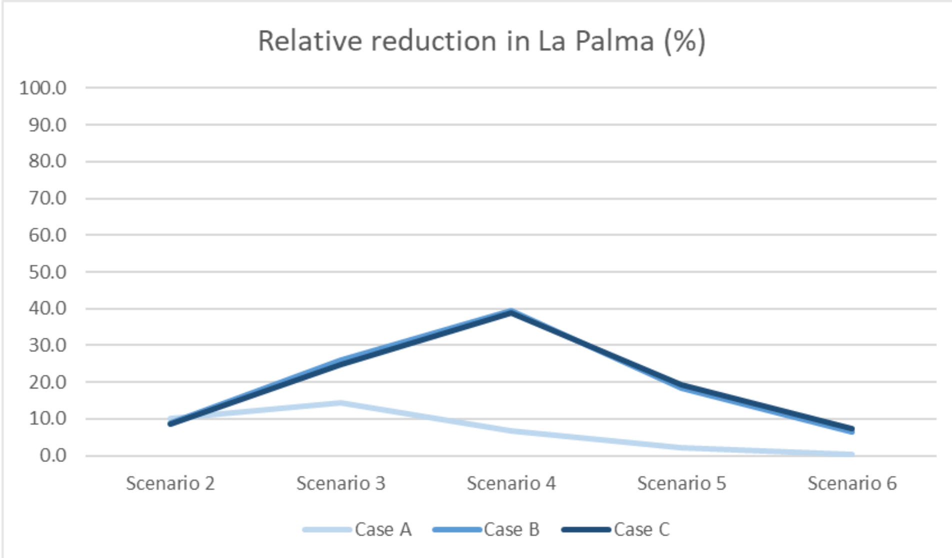

Figure 17: Relative cost reduction in La Palma

Finally, Figure 18 displays wind spillages in La Palma. Although, as expected, spillages are greater for higher installed wind capacity, it is evidenced that spillages are lessened when wind is allowed to provide reserve.

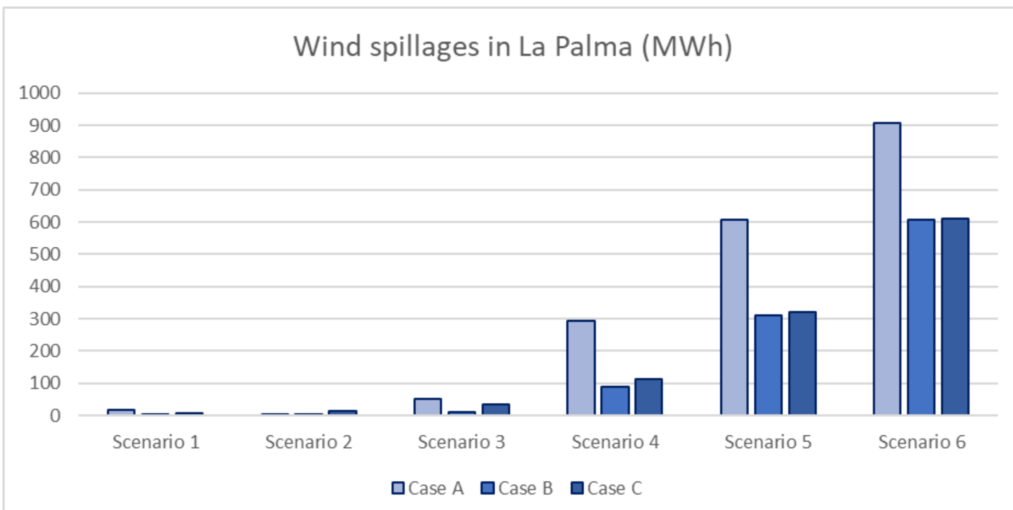

Figure 18: Daily wind spillages in La Palma (MWh)

All in all, as aforementioned, a huge change in the system behaviour is reflected in the costs of Scenario 4 (ten times the current installed wind capacity) with respect with the prior scenario (five times the current installed wind capacity). This can be justified in the much lower output required by conventional generators in Scenario 4 (Figure 20) in comparison with Scenario 3 (Figure 19), as well as in the reduction of the number of start-ups and shut downs needed to operate the system (Figure 21 and Figure 22).

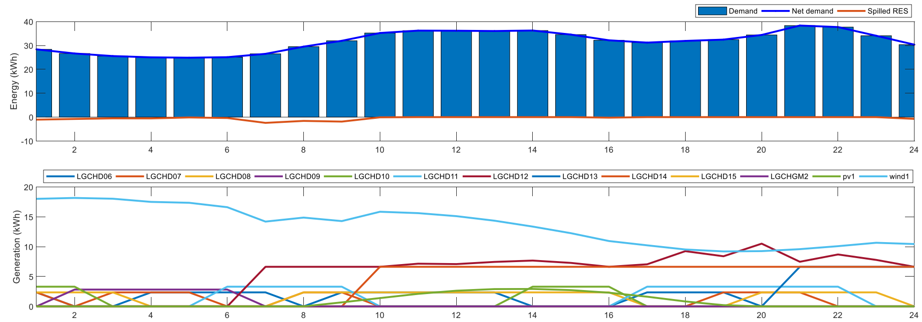

Figure 19: Demand curve and thermal generators' output in Scenario 3 (Case B)

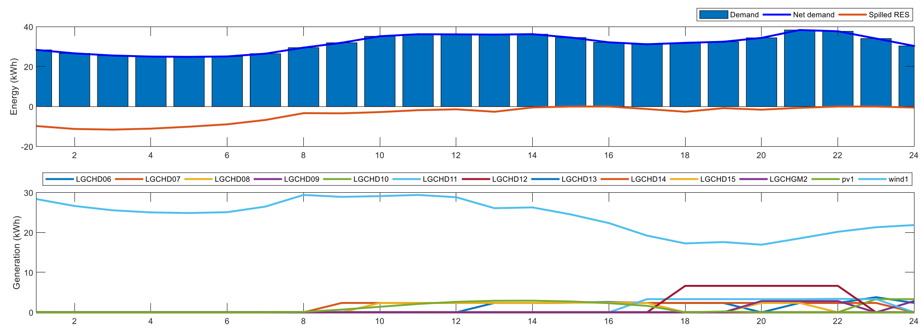

Figure 20: Demand curve and thermal generators' output in Scenario 4 (Case B)

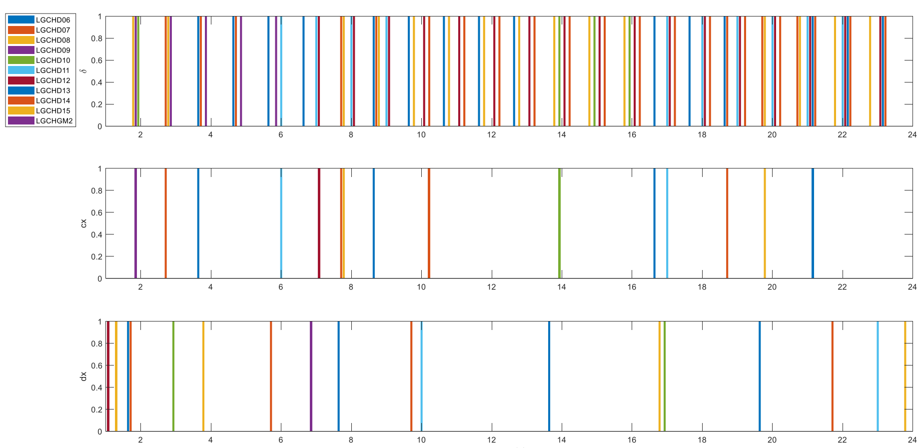

Figure 21: Start-ups and shut downs for Scenario 3 and Case B in La Palma

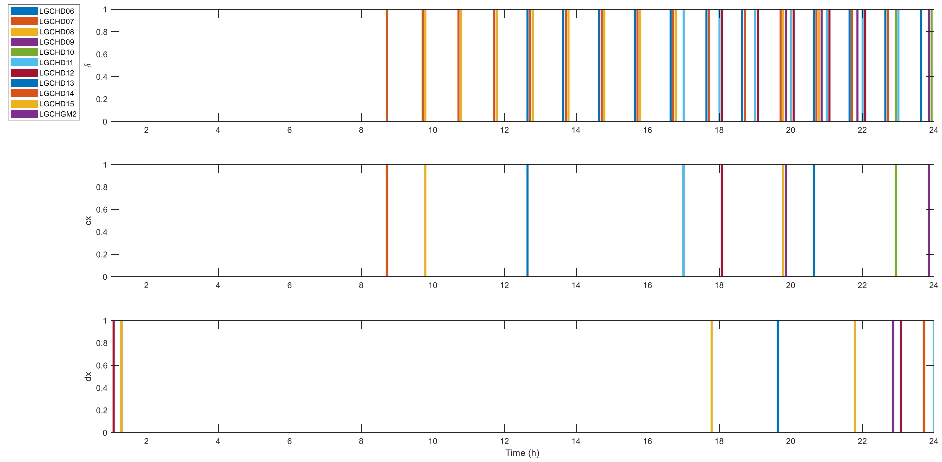

Figure 22: Start-ups and shut downs for Scenario 4 and Case B in La Palma

To conclude the analysis for La Palma, a whole week has been simulated to provide strongly supported conclusions. As can be observed from Figure 23, Figure 24 and Figure 25, the same behaviour as in the daily analysis is observed for the whole week. Therefore, the conclusions drawn from the previous graphs can be extrapolated to the whole week and, in general, to the operation of the electric system of La Palma.

The complete numerical results obtained for the whole week can be found in **Annex: Numerical results**.

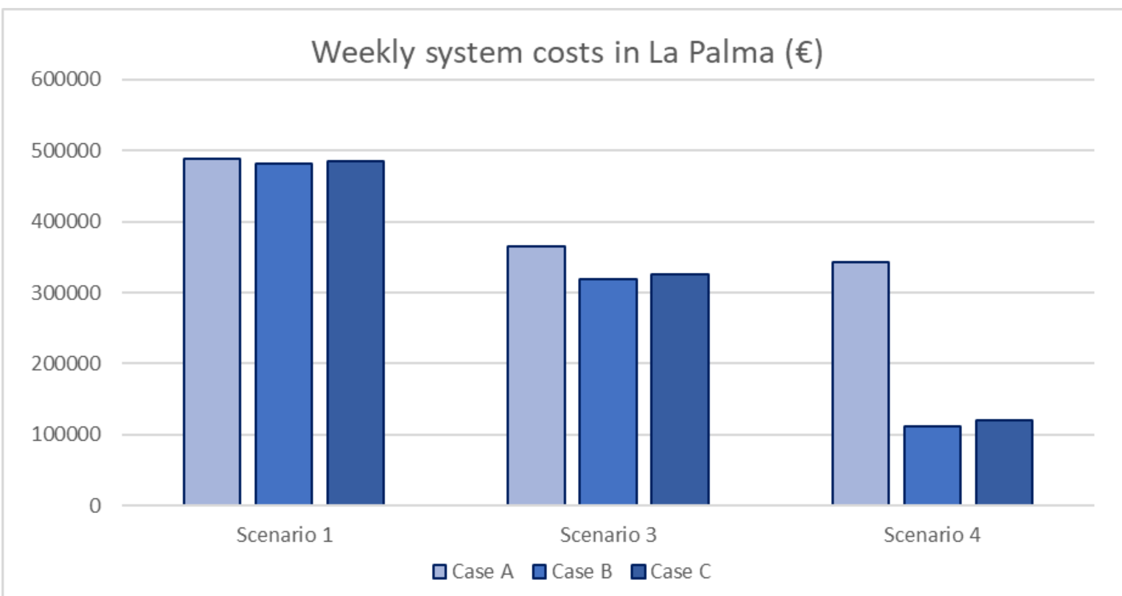

Figure 23: Weekly total dispatch costs in La Palma (€)

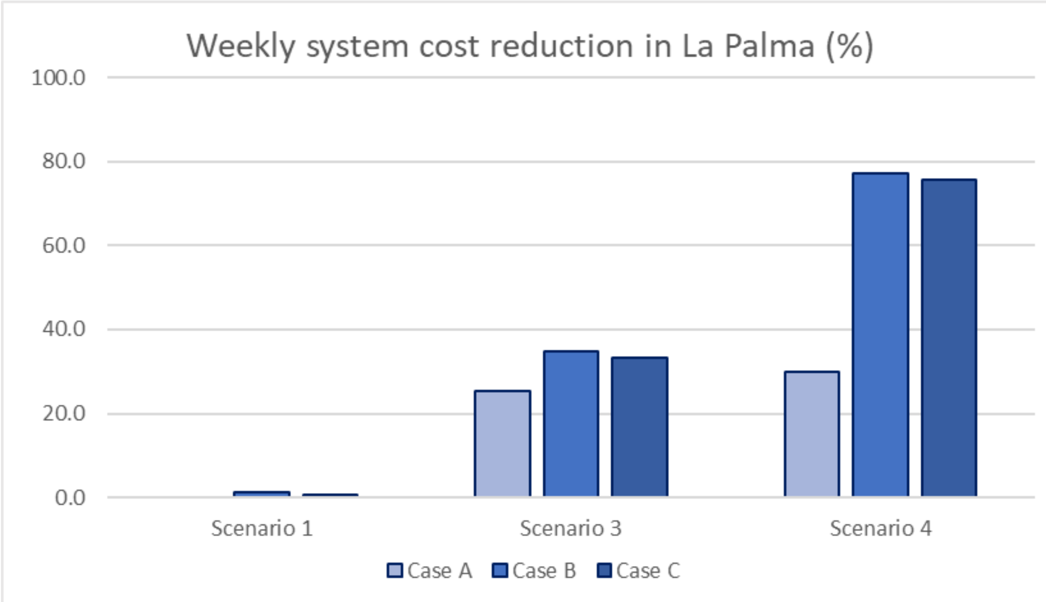

Figure 24: Weekly system costs reduction in La Palma (compared to current scenario and Case A)

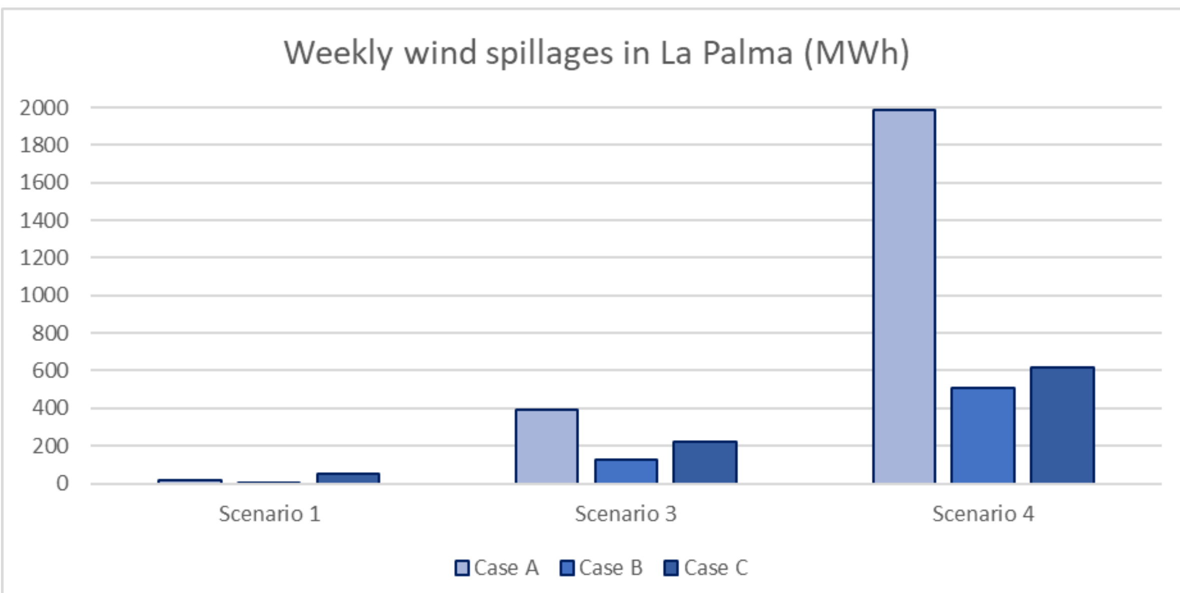

Figure 25: Weekly wind spillages in La Palma (MWh)

4.3.2. Gran Canaria

Analogously to the simulations for La Palma, total dispatch costs obtained for Gran Canaria are summarized in Table 7 and shown in Figure 26. In the case of Gran Canaria, only three scenarios (current, twice and five times the current installed wind capacity) have been computed due to the more complex calculations required by this system, greater than La Palma.

	Case A	Case B	Case C
Scenario 1	901015	898394	907538
Scenario 2	807585	727190	765555
Scenario 3	516672	268075	287027

Table 7: Total cost of dispatch in Gran Canaria (€)

A more detailed decomposition of the numerical results is shown in **Annex: Numerical results**.

Similarly to what happened in La Palma, from Table 7 and graphically from Figure 26, it can be seen that any increase on wind installed capacity brings benefits to the cost of the dispatch, independently of the paper that this type of renewable energy develops in the ancillary services. Again, this benefit is greater in each scenario when allowing wind power to provide reserve without limiting this reserve to any specific percentage. Moreover, for the island of Gran Canaria, a huge improvement is found in Scenario 3 with regard to Scenario 2.

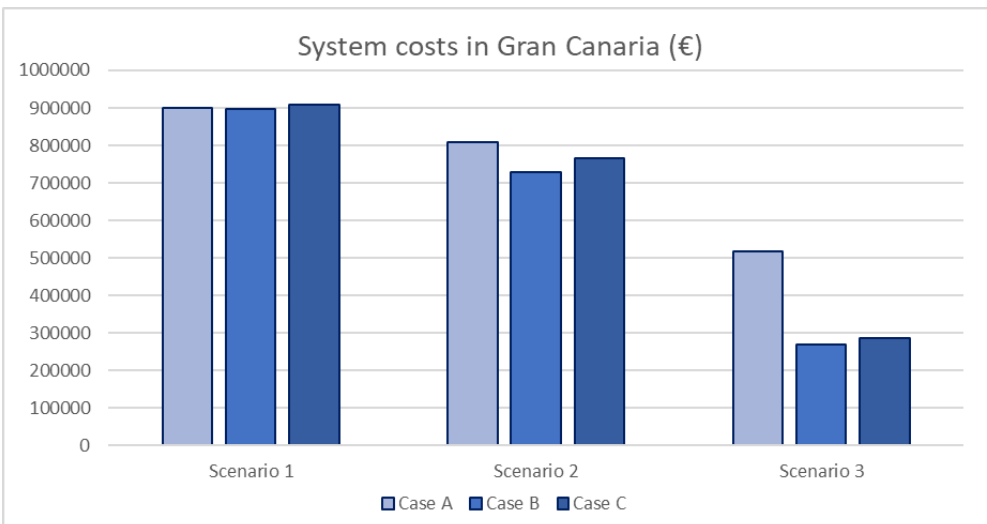

Figure 26: Total dispatch costs in Gran Canaria (€)

Figure 27 displays system cost reduction as a percentage with regard to the current scenario not allowing wind power to provide reserves. It is highlightable that between Scenario 2 and Scenario 3 when allowing wind power to participate in the ancillary services (Case B) there is an improvement of 51%, compared to a much lower 19% between Scenario 1 and Scenario 2 for the same case. In Scenario 1 only case B means a cost reduction in the dispatch, as Case A sets the reference value to calculate the percentage and Case C is more expensive than Case A in this scenario.

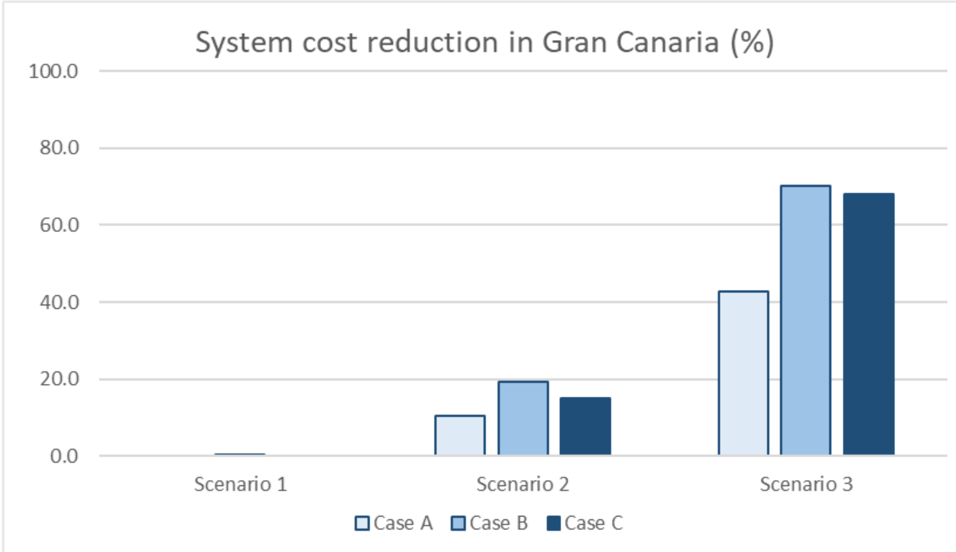

Figure 27: System cost reduction in Gran Canaria (compared to current scenario and Case A)

Lastly, when comparing each scenario with the directly previous one for each case (A, B and C), the same tendency is observed, as reflected in Figure 28. It is important to notice that, even though per the results in Scenario 3 it seems that Case C brings the greatest reduction with respect to Scenario 2 Case C, Table 7 shows that, in real terms, Case B in Scenario 2 is the optimal solution.

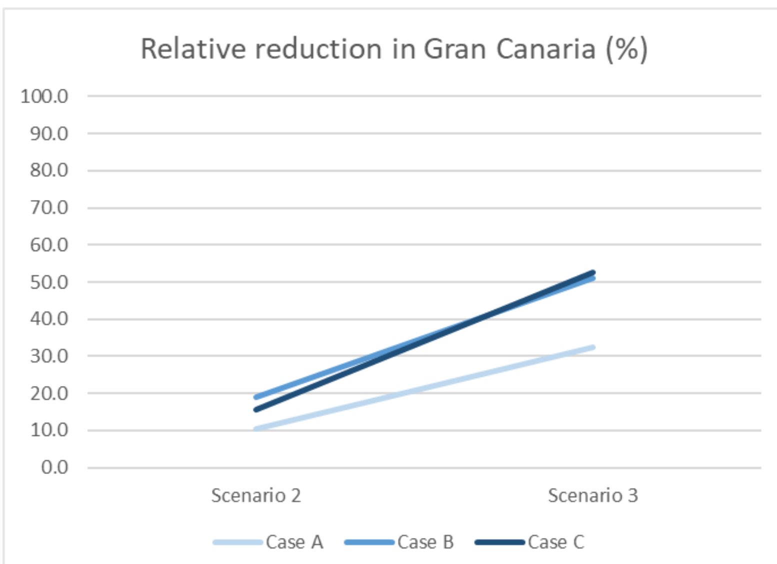

Figure 28: Relative cost reduction in Gran Canaria

Finally, wind spillages for each simulation in Gran Canaria are shown in Figure 29. It seems evident that the greatest exploitation of wind occurs when this energy is allowed to participate in the ancillary services. This fact is even more noticeable in Scenario 3. Even though in La Palma (Figure 18) the difference in Case B was evident in comparison to the current situation (Case A) - especially for scenarios 4, 5 and 6 - differences in the exploitation of wind power were not so big between Case B and Case C, while the advantages regarding wind spillages are more significant in Gran Canaria for Case B in Scenario 3, compared both to Case A and Case C.

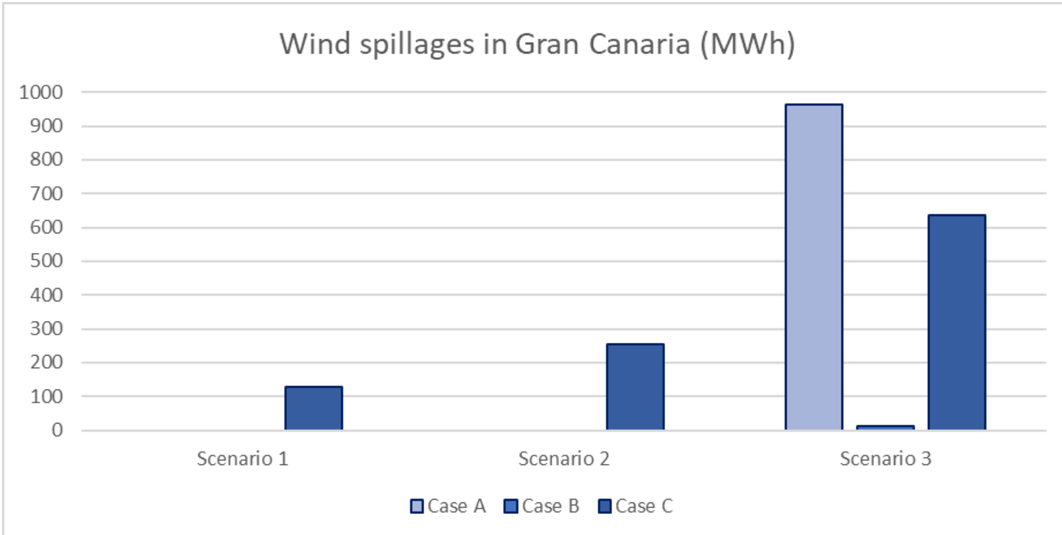

Figure 29: Daily wind spillages in Gran Canaria (MWh)

Finally, a whole week has been analysed in the island of Gran Canaria. As happened in the case of La Palma, it can be observed in Figure 26, Figure 27 and Figure 28 that also for Gran Canaria the same tendency as in the daily analysis is followed for the weekly results. It is shown how the higher the wind installed capacity the lower the dispatch costs are and, moreover, dispatch costs are the lowest for Case B in any of the scenarios proposed. As has been exposed, the best solution would be obtained for Scenario 3 with Case B settings. Therefore, again, the conclusions drawn from the previous graphs can be extrapolated to the whole week and, in general, to the operation of the electric system of Gran Canaria.

The complete numerical results obtained for the whole week can be found in **Annex: Numerical results**.

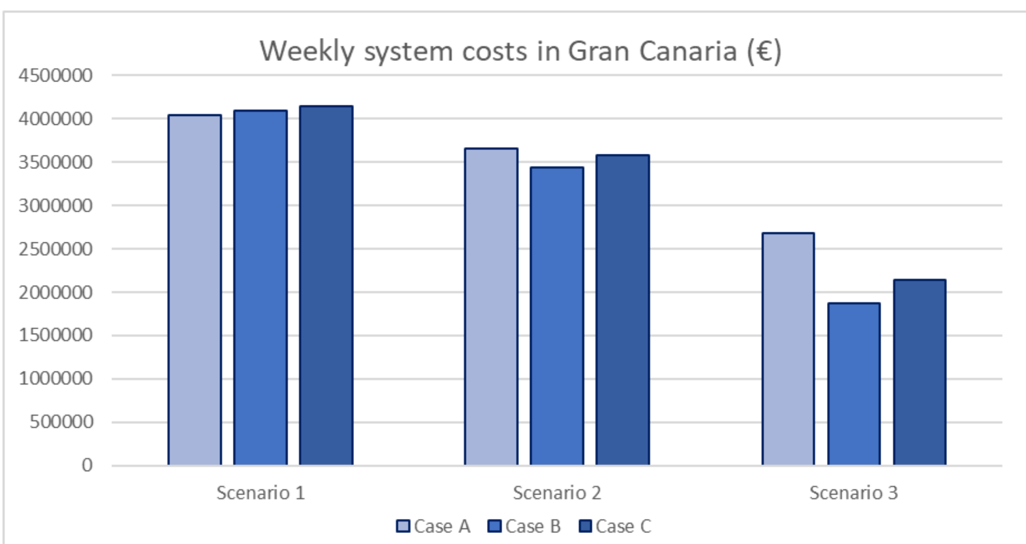

Figure 30: Weekly total dispatch costs in Gran Canaria (€)

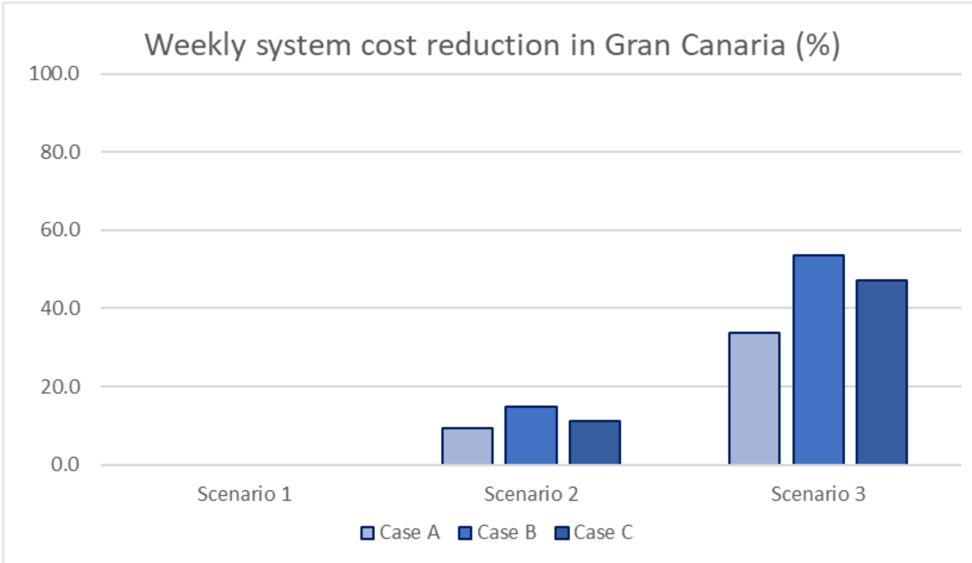

Figure 31: Weekly system costs reduction in Gran Canaria (compared to current scenario and Case A)

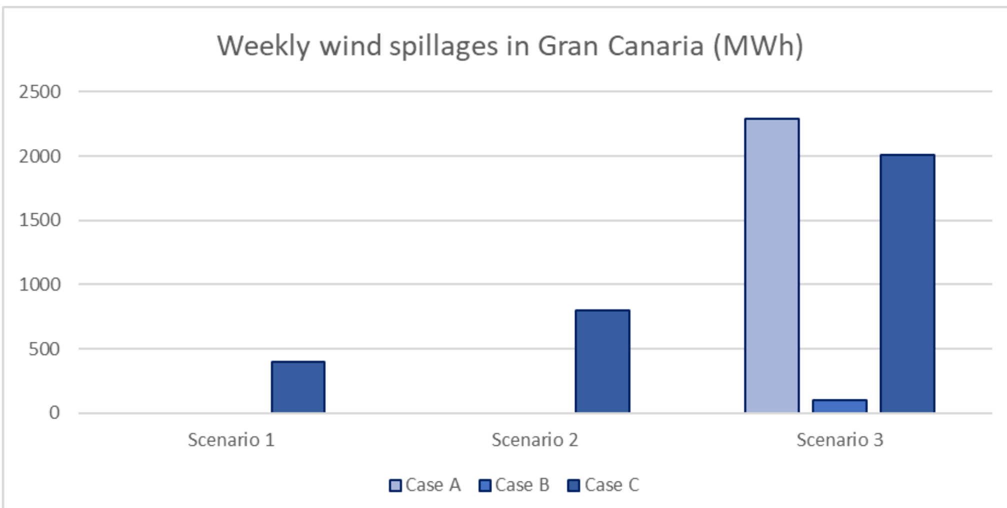

Figure 32: Weekly wind spillages in Gran Canaria (MWh)

4.4. Sensitivity analysis

4.4.1. La Palma

The sensitivity analysis was carried out for Scenario 6. Total costs for the sensitivity analysis in La Palma are as shown in Table 8 and Figure 33.

	Case A	Case B	Case C
Scenario 6.1	47,216	595	968
Scenario 6.2	47,216	595	968
Scenario 6.3	50,055	1,684	1,684

Table 8: Sensitivity analysis in La Palma. Total cost of dispatch (€)

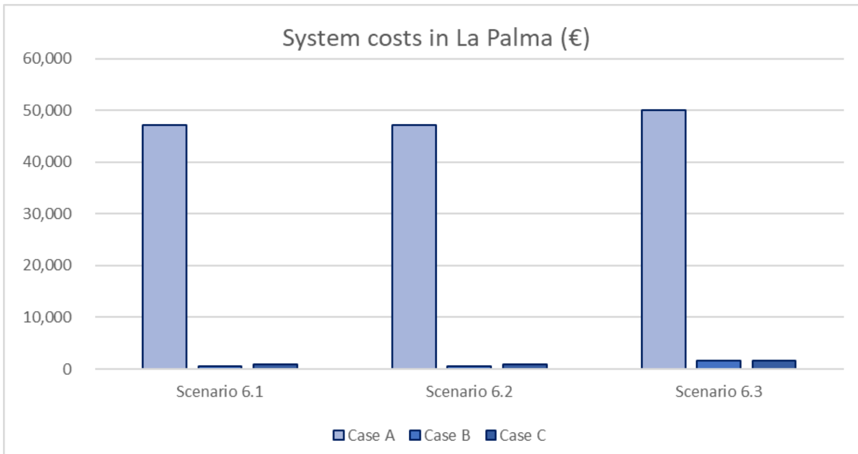

Figure 33: Sensitivity analysis in La Palma. Total cost of dispatch (€)

Analogously to the previous analysis, the cheapest solution is obtained when allowing RES to provide reserve without deloading wind (Case B), independently of the value of the RES loss coefficient. Also, as reflected in Table 8 and as could be expected, the higher the amount of RES variation to be covered by the reserves, the greater the cost of the dispatch. However, between Scenario 6.1 and Scenario 6.2 the results provided by the model are not enough to determine a good conclusion. The similarities between both scenarios could be due to the fact that the change in the reserve caused by the percentage of wind variation considered (from 10% to 5%) in La Palma might not be enough to enable the shutdown of a thermal power plant.

4.4.2. Gran Canaria

The sensitivity analysis was performed in Gran Canaria for Scenario 3 (five times the current installed wind capacity). Total costs are shown in Table 9 and Figure 34.

	Case A	Case B	Case C
Scenario 3.1	537,069	251,676	285,335
Scenario 3.2	516,672	268,075	287,027
Scenario 3.3	539,657	260,122	287,421

Table 9: Sensitivity analysis in Gran Canaria. Total cost of dispatch (€)

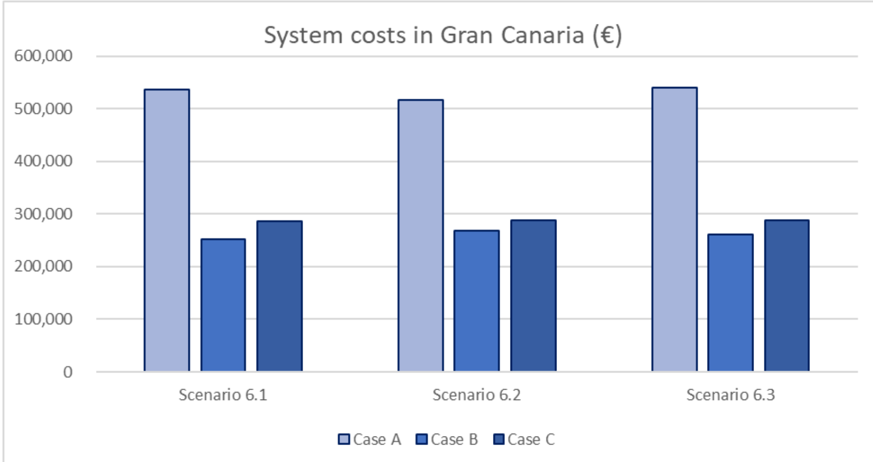

Figure 34: Sensitivity analysis in Gran Canaria. Total cost of dispatch (€)

Again, it is proven that the cheapest solution is obtained when allowing RES to provide reserve without deloading wind (Case B), independently of the value of the RES loss coefficient. However, Table 9 reflects that results are not so intuitive when systems are more complex. The outlier result of Scenario 6.1 for Case A might be due to the higher tolerance of the solution (Table 25), so it could still be considered that results show how the higher the amount of RES variation to be covered by the reserves, the greater the cost of the dispatch.

Finally, it could be concluded that differences between the percentage of RES loss variation taken into account does not drive to such differences in dispatch costs as the improvements driven by letting RES participate in the ancillary services.

4.5. Partial conclusions

From the previous results, it definitely seems profitable to allow renewable energy sources to provide spinning reserve in islanded systems.

In the different performed simulations, the fact that Case B always provides the lowest dispatch cost regardless of the evaluated scenario is remarkable. The same tendency was observed when the sensitivity analysis was conducted.

As expected, benefits are higher when the installed wind capacity is higher. Even though the particularities of these systems may not enable to install as RES capacity as desirable, it is clear that the higher RES penetration the cheaper the dispatch will be. Again, system costs will be even lower if RES are enabled to provide spinning reserve.

Lastly, regarding the sensitivity analysis, it could be highlightable that the higher the percentage of RES loss considered, the costlier the dispatch is. Nevertheless, dispatch costs for Case B have nothing to do with those for Case A: regardless of the percentage of RES loss considered for the reserve, Case B drives to much cheaper solutions than Case A, showing the strong benefits that allowing RES to provide reserve could bring to the system, independently of the RES loss coefficient.

5. Conclusions

In islanded systems, enough conventional groups need to be left connected in case reserve was necessary. In this situation, it is complex that the dispatch costs decrease below a specific range, as conventional generation is more expensive than renewable energies. However, when allowing wind energy to participate in the spinning reserve and if the penetration of renewables is high enough, the electric system in the islands could reach a situation where conventional generation – or at least not as many conventional groups as nowadays - is not necessary to be permanently connected anymore and, therefore, system dispatch costs would be greatly reduced.

In this context, this Master Thesis aimed to determine the economic impact that renewable energies providing spinning reserve have on islanded electric systems. To do so, different penetration scenarios of renewable energies have been analysed, establishing as main objective the economic valuation of the service provided, as allowing renewable energies to provide spinning reserve will imply a variation of the generation from thermal plants and, therefore, it will have an economic impact in the dispatch.

With this purpose, a model of the economic operation of islands has been developed, that allows simulating the unit commitment of island systems. This model has been applied to two Spanish isolated power systems: the islands of La Palma and Gran Canaria. Different scenarios have been simulated, varying the renewable generation profile and considering both that RES are and are not allowed to provide spinning reserve. Total costs for the dispatch have been obtained for each simulation performed.

From the analysis performed in this Master Thesis, it has been shown that allowing renewable energies to participate in the spinning reserve brings high benefits to islanded electric systems. System costs are lower for any scenario when renewable energies actively participate in the ancillary services. For both La Palma and Gran Canaria, it has been observed that above a specific level of share of renewable energies it definitely compensates to allow renewable resources to participate in this ancillary service.

In this sense, as has been mentioned, electricity tariffs in the islanded systems are identical to those in the Iberian Peninsula, although generation costs are much more expensive in the first ones. This is achieved by socializing the extra costs of this generation to all electricity consumers: the so-called compensation to non-peninsular systems. Therefore, by cheapening dispatch costs in the islanded systems, the whole electricity system in the country is perceiving benefits, as the compensation to extra peninsular systems would be diminished.

Moreover, it is understandable that the particularities of these territories – such as limited developable land for the case of solar and onshore wind energy – might not enable the installation of as much RES capacity as would seem optimal for the dispatch, but even so installing as much RES as feasible would definitely lower system costs, even to a greater extent if renewables provide spinning reserve. What is more, when permitting this, RES exploitation is optimized and wind energy spillages are minimized. In this aspect, the Canary Islands' commitment to renewable energy projects has been reflected in **Actual and future RES capacity**.

All in all, results provided in this Master Thesis hold the profitability of enabling renewable generation to participate in ancillary services by providing spinning reserve in islanded systems. By doing this, islanded systems' generation costs would be lowered, bringing benefits to all customers as the compensation to non-peninsular systems would be reduced. Moreover, the role of renewable energies in islanded systems would gain importance, taking a step forward in reducing CO_2 emissions and opening the door to a 100% renewable system.

6. References

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7. Annex: Numerical results

In this section, the numerical results obtained in each simulation performed are specified. The costs of the dispatch are split on an LP solution (referring to the Linear Programming result) and a MILP solution (in reference to the Mixed Integer Linear Programming Result). Moreover, the tolerance of each solution is shown, together to the wind spillages associated to each simulation.

Results are split in two subsections, reflecting the obtained results for each island: La Palma and Gran Canaria. Each subsection details the results obtained for the daily and weekly analysis, as well as those derived from the sensitivity study.

7.1. La Palma

The daily analysis in La Palma provided the results that are contained in Table 10, Table 11 and Table 12.

	LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Scenario 1	67,305	71,569	2.9%	16.1
Scenario 2	60,534	64,324	2.7%	2.5
Scenario 3	47,458	53,938	5.9%	52.1
Scenario 4	42,927	49,134	5.8%	293.4
Scenario 5	42,553	47,554	4.6%	608.5
Scenario 6	42,553	47,216	4.0%	906.3

Table 10: Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case A in La Palma

	LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Scenario 1	67,305	69,347	1.0%	1.4
Scenario 2	60,523	63,220	1.6%	0.2
Scenario 3	40,380	45,187	4.5%	10.0
Scenario 4	14,464	17,850	8.2%	87.9
Scenario 5	3,467	5,035	0.0%	310.7
Scenario 6	215	595	0.0%	607.9

Table 11: Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case B in La Palma

	LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Scenario 1	67,886	69,739	0.8%	6.7
Scenario 2	61,687	63,825	1.0%	13.4
Scenario 3	43,294	46,622	2.9%	34.6
Scenario 4	17,715	19,557	2.4%	112.7
Scenario 5	5,212	6,131	0.0%	322.4
Scenario 6	772	968	0.0%	611.7

Table 12: Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case C in La Palma

Weekly results for the island of La Palma are reflected in Table 13, Table 14 and Table 15.

		LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Day 1	Scenario 1	67,305	71,855	3.1%	16.1
	Scenario 3	48,079	52,998	4.5%	0.1
	Scenario 4	42,927	49,134	5.8%	293.4
Day 2	Scenario 1	65,691	69,146	2.5%	0.0
	Scenario 3	45,591	50,717	5.0%	29.5
	Scenario 4	42,192	48,098	5.5%	197.5
Day 3	Scenario 1	65,862	68,063	1.5%	0.0
	Scenario 3	44,929	52,944	7.9%	60.1
	Scenario 4	42,836	47,016	3.7%	268.2
Day 4	Scenario 1	67,169	69,477	1.5%	2.1
	Scenario 3	46,334	52,649	6.2%	50.3
	Scenario 4	43,872	50,235	6.1%	295.1
Day 5	Scenario 1	67,672	70,854	2.2%	0.0
	Scenario 3	46,442	52,398	5.9%	73.6
	Scenario 4	44,109	49,140	4.6%	279.4
Day 6	Scenario 1	67,899	70,306	1.6%	0.0
	Scenario 3	46,435	51,442	4.8%	67.8
	Scenario 4	44,345	48,509	3.7%	294.7
Day 7	Scenario 1	66,710	68,284	1.0%	0.0
	Scenario 3	45,716	51,386	5.5%	110.5
	Scenario 4	43,953	49,948	5.7%	357.9

Table 13: Weekly analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case A in La Palma

		LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Day 1	Scenario 1	67,305	69,487	1.0%	1.4
	Scenario 3	40,380	46,706	6.3%	0.1
	Scenario 4	14,464	17,850	8.2%	87.9
Day 2	Scenario 1	65,691	67,639	0.8%	0.0
	Scenario 3	42,863	48,157	5.0%	30.8
	Scenario 4	15,319	23,201	16.8%	54.1
Day 3	Scenario 1	65,862	68,707	1.5%	0.0
	Scenario 3	39,491	44,648	5.1%	8.7
	Scenario 4	8,791	15,928	21.0%	69.3
Day 4	Scenario 1	67,169	69,206	0.9%	0.0
	Scenario 3	39,674	45,398	5.8%	21.2
	Scenario 4	9,711	15,177	17.6%	75.1
Day 5	Scenario 1	67,672	69,608	0.9%	1.7
	Scenario 3	40,516	44,093	3.2%	6.7
	Scenario 4	9,678	14,273	13.5%	58.4
Day 6	Scenario 1	67,899	69,486	0.6%	2.3

	Scenario 3	40,140	46,027	6.0%	40.7
	Scenario 4	8,617	13,525	14.8%	59.9
Day 7	**Scenario 1**	66,710	68,093	0.6%	0.0
	Scenario 3	36,813	42,927	6.5%	15.2
	Scenario 4	6,542	11,411	20.3%	104.4

Table 14: Weekly analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case B in La Palma

		LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Day 1	**Scenario 1**	67,886	70,145	1.0%	6.7
	Scenario 3	43,294	46,143	2.0%	0.1
	Scenario 4	17,715	19,557	2.4%	112.7
Day 2	**Scenario 1**	66,181	68,253	0.9%	6.8
	Scenario 3	45,326	50,607	4.8%	30.5
	Scenario 4	19,869	23,288	6.0%	64.2
Day 3	**Scenario 1**	66,429	68,377	0.9%	6.5
	Scenario 3	42,333	46,153	3.5%	33.7
	Scenario 4	13,086	15,464	4.7%	70.3
Day 4	**Scenario 1**	67,761	69,404	0.8%	6.8
	Scenario 3	42,648	45,295	1.7%	35.7
	Scenario 4	13,539	15,484	4.2%	85.5
Day 5	**Scenario 1**	68,256	69,801	0.6%	6.7
	Scenario 3	43,454	47,091	3.3%	37.9
	Scenario 4	13,740	16,051	4.3%	76.8
Day 6	**Scenario 1**	68,495	70,185	0.6%	8.3
	Scenario 3	43,142	46,141	2.5%	39.8
	Scenario 4	12,704	17,784	14.9%	98.1
Day 7	**Scenario 1**	67,355	68,963	0.7%	7.4
	Scenario 3	40,052	44,476	4.3%	45.2
	Scenario 4	10,030	11,931	4.8%	111.6

Table 15: Weekly analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case C in La Palma

After performing the sensitivity analysis, detailed results for Scenario 6 for La Palma are included in Table 16, Table 17 and Table 18.

	LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Scenario 6.1	42,553	47,216	4.0%	906.3
Scenario 6.2	42,553	47,216	4.0%	906.3
Scenario 6.3	46,350	50,055	3.5%	930.9

Table 16: Sensitivity analysis: total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case A in La Palma

	LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Scenario 6.1	215	595	0.0%	607.9
Scenario 6.2	215	595	0.0%	607.9
Scenario 6.3	962	1,684	0.0%	617.3

Table 17: Sensitivity analysis: total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case B in La Palma

	LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Scenario 6.1	772	968	0.0%	611.7
Scenario 6.2	772	968	0.0%	611.7
Scenario 6.3	962	1,684	0.0%	617.3

Table 18: Sensitivity analysis: total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case C in La Palma

7.2. Gran Canaria

The daily analysis in Gran Canaria provided the results that are contained in Table 19, Table 20 and Table 21. In the case of Gran Canaria, some results might be missing because the model was not able to provide a solution within the requirements (specified tolerance and solution time) due to the higher complexity of this system.

	LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Scenario 1	735,965	901,015	9.4%	0.0
Scenario 2	626,626	807,585	12.0%	0.0
Scenario 3	467,800	516,672	4.7%	962.7

Table 19: Daily analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case A in Gran Canaria

	LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Scenario 1	735,965	898,394	8.9%	0.0
Scenario 2	598,731	727,190	9.1%	0.0
Scenario 3	221,994	268,075	8.1%	11.5

Table 20: Daily analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case B in Gran Canaria

	LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Scenario 1	747,610	907,538	8.8%	127.4
Scenario 2	621,335	765,555	10.0%	254.7
Scenario 3	272,395	287,027	1.2%	636.9

Table 21: Daily analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case C in Gran Canaria

Weekly results for the island of Gran Canaria are reflected in Table 22, Table 23 and Table 24.

		LP (€)	MILP (€)	Tolerance	Spillages (MWh)
Day 1	**Scenario 1**	735,965	901,015	9.4%	0.0
	Scenario 2	626,626	807,585	12.0%	0.0
	Scenario 3	467,800	516,672	4.7%	962.7
Day 2	**Scenario 1**	690,996	978,678	16.7%	0.0
	Scenario 2	583,714	704,776	8.8%	9.2
	Scenario 3	431,598	601,339	16.2%	1,261.7
Day 3	**Scenario 1**	796,149	990,335	10.3%	0.0
	Scenario 2	681,334	853,945	10.7%	0.0
	Scenario 3	514,264	611,860	8.6%	1,159.5
Day 4	**Scenario 1**	838,147	1,041,604	10.0%	0.0
	Scenario 2	736,223	846,894	6.0%	0.0
	Scenario 3	551,010	659,016	8.5%	377.0

Day 5	**Scenario 1**	889,290	1,112,191	10.2%	0.0
	Scenario 2	829,811	1,087,652	12.6%	0.0
	Scenario 3	685,117	819,197	8.0%	0.0
Day 6	**Scenario 1**	876,910	-	-	-
	Scenario 2	805,272	978,020	8.8%	0.0
	Scenario 3	646,203	807,083	10.5%	7.8
Day 7	**Scenario 1**	853,652	1,034,541	8.9%	0.0
	Scenario 2	762,472	915,136	8.1%	0.0
	Scenario 3	574,312	732,906	11.5%	166.1

Table 22: Weekly analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case A in Gran Canaria

		LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Day 1	**Scenario 1**	735,965	898,394	8.9%	0.0
	Scenario 2	598,731	727,190	9.1%	0.0
	Scenario 3	221,994	268,075	8.1%	11.5
Day 2	**Scenario 1**	690,996	814,970	7.4%	0.0
	Scenario 2	564,625	676,412	8.4%	0.0
	Scenario 3	220,095	272,497	10.0%	0.0
Day 3	**Scenario 1**	796,149	993,830	10.1%	0.0
	Scenario 2	651,086	795,066	9.2%	0.0
	Scenario 3	250,496	268,788	2.5%	90.5
Day 4	**Scenario 1**	838,147	1,077,195	11.4%	0.0
	Scenario 2	725,387	867,309	8.0%	0.0
	Scenario 3	402,851	429,047	2.2%	42.1
Day 5	**Scenario 1**	889,290	1,158,756	12.0%	0.0
	Scenario 2	829,811	964,282	6.5%	0.0
	Scenario 3	658,512	772,030	7.0%	0.0
Day 6	**Scenario 1**	876,910	1,133,266	11.6%	0.0
	Scenario 2	805,272	965,861	7.9%	0.0
	Scenario 3	598,150	726,612	9.0%	0.0
Day 7	**Scenario 1**	853,652	1,045,807	9.1%	0.0
	Scenario 2	759,474	952,307	10.2%	0.0
	Scenario 3	487,404	565,246	6.9%	0.0

Table 23: Weekly analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case B in Gran Canaria

		LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Day 1	**Scenario 1**	747,610	907,538	8.8%	127.4
	Scenario 2	621,335	765,555	10.0%	254.7
	Scenario 3	272,395	287,027	1.2%	636.9
Day 2	**Scenario 1**	701,787	-	-	-
	Scenario 2	585,218	674,490	6.7%	235.6
	Scenario 3	267,045	323,280	8.9%	589.1

Day 3	**Scenario 1**	808,239	984,850	8.9%	134.8
	Scenario 2	674,967	831,118	9.6%	269.6
	Scenario 3	300,993	309,856	0.7%	676.0
Day 4	**Scenario 1**	847,574	962,484	5.2%	103.5
	Scenario 2	-	-	-	-
	Scenario 3	446,132	463,209	1.0%	517.4
Day 5	**Scenario 1**	894,218	1,100,592	9.0%	53.5
	Scenario 2	839,428	1,114,082	13.1%	107.1
	Scenario 3	681,906	917,576	14.0%	267.6
Day 6	**Scenario 1**	882,828	990,114	4.4%	64.2
	Scenario 2	816,919	977,716	7.8%	128.4
	Scenario 3	626,472	704,950	5.2%	321.0
Day 7	**Scenario 1**	861,511	1,153,528	13.6%	85.3
	Scenario 2	774,877	875,365	5.0%	170.6
	Scenario 3	524,229	623,236	8.1%	426.5

Table 24: Weekly analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case C in Gran Canaria

After performing the sensitivity analysis, detailed results for Scenario 3 for Gran Canaria are included in Table 25, Table 26 and Table 27.

	LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Scenario 6.1	450,984	537,069	8.4%	1,052.4
Scenario 6.2	467,800	516,672	4.7%	962.7
Scenario 6.3	500,662	539,657	3.5%	1,403.3

Table 25: Sensitivity analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case A in Gran Canaria

	LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Scenario 6.1	221,664	251,676	5.2%	4.2
Scenario 6.2	221,994	268,075	8.1%	11.5
Scenario 6.3	225,907	260,122	6.0%	21.6

Table 26: Sensitivity analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case B in Gran Canaria

	LP (€)	**MILP (€)**	**Tolerance**	**Spillages (MWh)**
Scenario 6.1	272,395	285,335	0.9%	636.9
Scenario 6.2	272,395	287,027	1.2%	636.9
Scenario 6.3	273,588	287,421	1.4%	636.9

Table 27: Sensitivity analysis. Total cost of dispatch (€), tolerance (%) and spillages (MWh) for Case C in Gran Canaria