BACHELOR’S DEGREE IN ENGINEERING FOR INDUSTRIAL TECHNOLOGIES

FINAL DEGREE PROJECT

Analysis of the economic dispatch of island electricity systems with safety and operational stability criteria

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Supervisor: Mohammad Rajabdorri

Co-Supervisor: Lukas Sigrist

Co-Supervisor: Enrique Lobato

Madrid, June 2021

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Análisis del despacho económico de sistemas eléctricos insulares con criterios de seguridad y estabilidad de la operación

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2020/21 es de mi autoría, original e inédito y

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ANÁLISIS DEL DESPACHO ECONÓMICO DE SISTEMAS ELÉCTRICOS INSULARES CON CRITERIOS DE SEGURIDAD Y ESTABILIDAD DE LA OPERACIÓN

Autor: Fuente Pascual, Delia.

Director: Rajabdorri, Mohammad; Lobato, Enrique y Sigrist, Lukas.

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RESUMEN DEL PROYECTO

Este trabajo analiza en qué circunstancias la provisión de reserva rodante por parte de la generación renovable proporciona beneficios técnicos y económicos a los sistemas eléctricos insulares. Los resultados muestran que, en escenarios de alta penetración de energía eólica, emplear un factor de descarga fijo permite reducir los costes de operación del sistema y mejorar la respuesta dinámica de la frecuencia, lo que se traduce en un menor coste de deslastre. Un factor de descarga variable, aunque supone unos costes operativos del sistema menores, no garantiza una respuesta de frecuencia fiable en determinados escenarios tras las contingencias. Para conseguir el mínimo coste del sistema y un buen comportamiento dinámico de la frecuencia, los sistemas reales deberían pasar a utilizar modelos de despacho económico que incluyan restricciones relacionadas con la frecuencia.

Palabras clave: Reserva; Despacho económico; Sistema eléctrico insular; Descarga de energía eólica; Reserva a bajar; Reserva a subir; Regulación de frecuencia

1. Introducción

Los sistemas eléctricos insulares se enfrentan a dos grandes problemáticas principales: un tamaño reducido y una débil o inexistente interconexión con otros sistemas eléctricos, lo cual los hace más vulnerables a las perturbaciones en la frecuencia y provoca mayores costes totales en la operación del sistema que en grandes sistemas interconectados.

El pequeño tamaño de estos sistemas repercute en su estabilidad de frecuencia, que depende fundamentalmente de la contingencia que se produzca, de la inercia del sistema y de la capacidad de control. Al haber menos unidades generadoras conectadas a la red, cada una de ellas cubre un alto porcentaje de la demanda total, y la inercia del sistema es pequeña. La pérdida de una de las unidades generadoras puede provocar una caída rápida de la frecuencia y conllevar a deslastres de carga si las protecciones de frecuencia no actúan a tiempo. Por ello, los requisitos de reserva son muy exigentes en relación con el tamaño de cada unidad.

Además, los sistemas eléctricos insulares no se benefician de la economía de escala presente en la generación. Por razones de seguridad, la capacidad instalada por grupo es pequeña, limitada, y generalmente menos eficiente. El mix de generación de estos sistemas eléctricos se basa en el gas, fuel y diesel, cuyos costes operativos son más elevados que los de otras fuentes convencionales, ya que la eficiencia de estas tecnologías es menor.

Actualmente, la generación renovable y en particular la eólica no proporciona reserva en el sistema, y por tanto hay unidades térmicas que deben estar permanentemente conectadas a la red para cumplir con los requisitos de reserva establecidos por la regulación española. Si participaran en la reserva, el escenario de generación cambiaría, reduciéndose la generación térmica y como consecuencia los costes de operación. Para poder proveer reserva y regulación de frecuencia, las turbinas eólicas deben trabajar por debajo de su punto de máxima generación considerando un factor de descarga.

Este trabajo de fin de grado tiene como objetivo principal analizar los impactos en la respuesta dinámica de la frecuencia en el sistema que supone considerar un factor de descarga eólica fijo y variable, así como su relación con los correspondientes impactos económicos. Para ello se empleará un modelo de despacho económico semanal y un modelo dinámico de frecuencia, y se analizarán distintos casos y escenarios de penetración de energía eólica. Con su consecución se contribuirá a los Objetivos de Desarrollo Sostenible 7 (Energía asequible y no contaminante), 11 (Ciudades y comunidades sostenibles) y 13 (Acción por el clima).

2. Metodología

La metodología empleada, véase Figura 1, simula la operación económica del sistema mediante un modelo de despacho económico semanal que determina tanto la generación por horas de cada unidad como sus decisiones de arranque y parada. Las entradas a este modelo incluyen la demanda semanal por hora, la generación renovable prevista y los datos de cada una de las unidades generadoras del sistema. Los resultados obtenidos se utilizan como entrada al modelo dinámico de frecuencia del sistema. En este modelo se simula la contingencia de cada unidad (incluida la eólica) que se encuentre conectada en cada hora de la semana, y se analiza la respuesta en frecuencia del sistema.

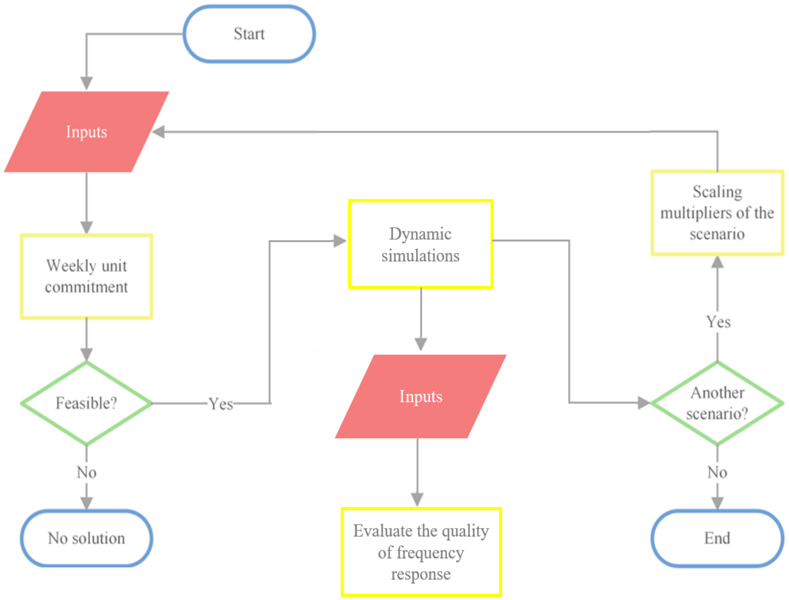

Figura 1. Diagrama de la metodología

El análisis se realizará para las islas de La Palma (tamaño pequeño) y Tenerife (tamaño mediano), las cuales han demostrado ser mediante técnicas de clustering dos de los cinco prototipos de islas existentes, por lo que estos resultados serán extrapolables a sistemas insulares del mundo entero. Además, se realizarán las simulaciones para una semana representativa de cada estación de los años 2020, 2025 y 2030, cuyos perfiles de demanda serán escalados, y para 4 escenarios de generación eólica. El escenario I contempla la cantidad actual de capacidad eólica instalada. Para los escenarios II a IV, la cantidad actual se multiplica por 2, 5 y 10, respectivamente. Para cada escenario, se definen los siguientes casos de provisión de reserva por parte de la generación eólica:

- Caso A: toda la reserva necesaria y la inercia del sistema debe ser proporcionada por las unidades térmicas, siendo el factor de descarga eólico cero.
- Caso B: se considera un factor de descarga de energía eólica fijo del 10% de la potencia disponible. También se incluye emulación de inercia.
- Caso C: se considera un factor de descarga de energía eólica variable entre el 0 y el 15%, y cuyo valor óptimo será decidido por el despacho económico. También se incluye emulación de inercia.

Además, para analizar la respuesta en frecuencia, todas las simulaciones se realizarán con y sin el esquema de deslastre de cargas actual activado.

3. Resultados

3.1. La Palma

La Figura 2 representa el número medio de casos graves totales ocurridos en el sistema ante la contingencia de cada una de las unidades generadoras conectadas (barras amarillas), el coste medio de operación diario (barras rojas) y el coste previsto de deslastre de carga en un año (barras verdes).

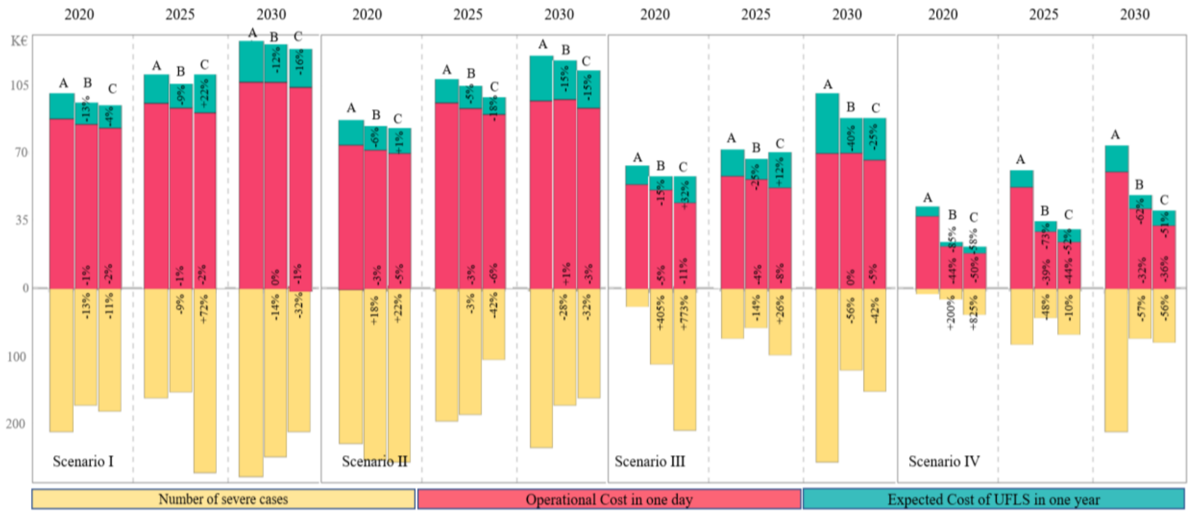

Figura 2. Media de los resultados técnicos y económicos obtenidos en las 4 estaciones del año en La Palma

Los resultados muestran que el coste total de generación es menor cuando se considera un factor de descarga, ya que en el caso base A hay unidades térmicas que deben estar permanentemente conectadas a la red únicamente para cubrir los requisitos de reserva, lo que hace que parte de la generación renovable se acabe vertiendo. Además, en los casos con descarga el número de unidades conectadas es menor ya que parte de la generación térmica puede ser desconectada.

Sin embargo, considerar un factor de descarga solo la mejora la respuesta en frecuencia si la demanda es elevada (años 2025 y 2030), ya que se conectan más unidades y la pérdida de una de ellas supone un menor impacto. Con una demanda baja y tratándose de una isla pequeña, hay muy pocos generadores conectados, por lo que la pérdida de uno de ellos tiene un gran impacto en la respuesta de la frecuencia del sistema. Cabe mencionar que comparar diferentes casos implica comparar diferentes despachos económicos, ya que las unidades conectadas varían de un caso a otro.

Además, los resultados muestran que el factor óptimo desde el punto de vista económico (caso C) no es necesariamente óptimo para la mejora de la respuesta en frecuencia. De hecho, el caso C no siempre mejora la respuesta en frecuencia del sistema y no tiene correlación con la demanda y la penetración eólica. Solo se produce descarga de generación eólica en las horas en las que no se ha programado suficiente reserva de generación térmica, lo que significa que se programa menos descarga para que sirva de reserva de potencia en comparación con el caso B. Cuando se produce una contingencia, al haber menos potencia para servir de reserva, la respuesta de la frecuencia puede empeorar.

Al activar el esquema de deslastre de cargas actual, se puede comprobar que la carga deslastrada es menor cuanto mejor es la respuesta en dinámica de la frecuencia. Para la misma demanda en los casos con descarga, la potencia deslastrada total en todas las contingencias se reduce al aumentar la penetración eólica. El motivo es porque, al proporcionar regulación de frecuencia, se mejora la respuesta dinámica del sistema y, por tanto, hay que deslastrar menos carga.

3.2. Tenerife

La Figura 3 representa el número medio de casos graves ocurridos en el sistema ante contingencias (barras amarillas), el coste medio de operación diario (barras rojas) y el coste previsto de deslastre de carga en un año (barras verdes).

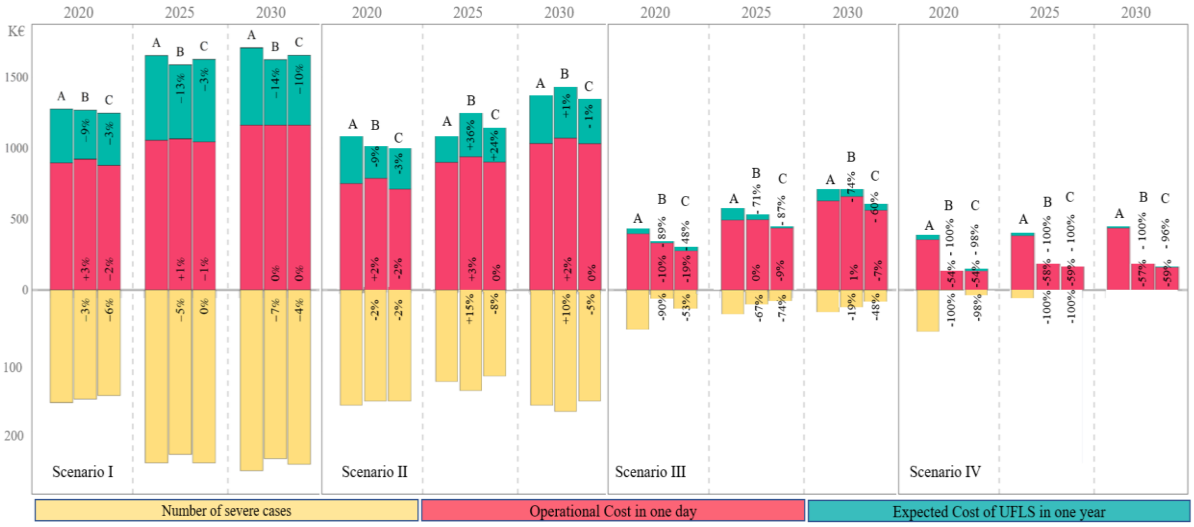

Figura 3. Media de los resultados técnicos y económicos obtenidos en las 4 estaciones del año en Tenerife

Los resultados muestran que la descarga siempre mejora la respuesta en frecuencia, pero, de nuevo, el factor de descarga óptimo desde el punto de vista económico no es necesariamente el valor que da la mejor respuesta en frecuencia.

En el caso B se considera un factor de descarga constante del 10%. De sus resultados se deduce que en algunas horas la descarga es innecesaria, ya que la respuesta en frecuencia empeora con respecto al caso A. Tener un factor de descarga constante tampoco es aconsejable desde el punto de vista económico cuando la penetración del viento es baja. Sin embargo, en esos casos concretos, tener un factor de descarga variable (caso C) sí mejora la respuesta y optimiza el coste total.

Los resultados también muestran que para los escenarios de penetración eólica futura la respuesta en frecuencia del sistema siempre mejora. Si además la energía eólica participa en la regulación de la frecuencia, dicha respuesta es muy buena y no se producen casos graves. Esto significa que no se necesitan deslastres de carga y que la red eléctrica es más segura y eficiente.

En general, el coste total (operativo y de posible deslastre) es mayor en el caso sin capacidad de descarga. El caso C es el que mejor resultados económicos proporciona, ya que considera el factor de descarga óptimo desde el punto de vista económico. Esto es especialmente notable en los escenarios de alta penetración eólica (III y IV), en los que se produce una gran reducción de costes, así como a una respuesta de frecuencia óptima. Se puede comprobar por tanto que un mayor número de casos graves se traduce en un mayor coste total.

Si se realizan las simulaciones con el esquema actual de deslastre de cargas, para la misma demanda y una alta penetración eólica, la potencia deslastrada total para todas las contingencias se mantiene constante en todos los casos. Esto ocurre incluso en el caso A, donde se habría esperado un aumento en este valor. La razón es porque, aunque las turbinas eólicas no proporcionen regulación de frecuencia, se conectan menos unidades, hay menos contingencias y hay que deslastrar menos carga. Además, a medida que aumenta la potencia eólica, el deslastre se reduce debido a una mejora en la respuesta de la frecuencia. En consecuencia, en los casos B y C el deslastre es menor que el caso base. En general, al igual que en las islas de pequeño tamaño, cuanto peor sea la respuesta en frecuencia, mayor será la cantidad de carga que habrá que deslastrar para no violar los límites de frecuencia impuestos por la normativa española. Al mejorar la respuesta en frecuencia, el coste previsto del deslastre disminuye.

4. Conclusiones

En este trabajo se demuestra que, bajo la práctica actual de los operadores del sistema y, de cara a fomentar la implementación de renovables en el futuro, es esencial contar con un factor de descarga de energía eólica fijo y no variable obtenido por el despacho económico, ya que este último no tiene en cuenta el comportamiento dinámico del sistema.

Los resultados obtenidos muestran que el factor de descarga es siempre beneficioso, tanto desde el punto de vista técnico como económico cuando el tamaño de la isla es mediano, como es el caso de Tenerife. Cuando la penetración eólica es elevada, la respuesta en frecuencia mejora, el sistema se vuelve más seguro y, en algunas horas, no es necesario deslastrar de carga. Como resultado, el coste total previsto debido al posible deslastre de carga se reduce, lo que supone un beneficio económico adicional. Se concluye entonces que los beneficios de proporcionar reserva con renovables en islas de tamaño mediano pueden aparecer inmediatamente si el factor de descarga considerado es el adecuado.

Por otro lado, en las islas pequeñas, el hecho de proporcionar regulación de frecuencia por parte de turbinas eólicas sólo mejora la respuesta de frecuencia cuando la demanda del sistema es alta. Dado su menor tamaño, cada unidad generadora cubre un alto porcentaje de la demanda total y, como consecuencia, la pérdida de una de ellas tiene un impacto considerable en la respuesta de frecuencia de todo el sistema. Por tanto, permitir que los generadores eólicos proporcionen regulación de frecuencia no es urgente en términos de mejorar la respuesta de la frecuencia, ya que los beneficios aparecerán cuando la demanda aumente en los próximos años.

Además, se demuestra que descargar energía eólica no es aconsejable en escenarios de baja penetración eólica. No obstante, considerando escenarios futuros en los que la demanda del sistema aumentará y dada la tendencia de los operadores del sistema a añadir más generación renovable, los resultados sugieren que emplear el factor de descarga adecuado es recomendable para mejorar la respuesta de frecuencia del sistema y reducir los costes totales de operación. Resulta interesante por tanto plantear modelos de despacho económico que incluyan restricciones relacionadas con la frecuencia para así optimizar tanto los costes como la respuesta dinámica del sistema.

En trabajos futuros se abordará el análisis de la respuesta en frecuencia bajo los futuros esquemas de deslastre óptimos, y se investigará la implementación de restricciones de frecuencia en despachos económicos con vistas a encontrar el factor de descarga variable que logre resultados óptimos tanto en la respuesta en frecuencia como en los costes totales del sistema.

ANALYSIS OF THE ECONOMIC DISPATCH OF ISLAND ELECTRICITY SYSTEMS WITH SAFETY AND OPERATIONAL STABILITY CRITERIA

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Collaborating Entity: IIT – Institute for Research in Technology.

ABSTRACT

This work analyses under what circumstances the provision of spinning reserve by renewable generation provides technical and economic benefits to real island power systems. The results show that, in scenarios of high wind power penetration, using a fixed deloading factor allows reducing system operating costs and improving system frequency response, which translates into a lower cost of derating. A variable unloading factor, while resulting in lower system operating costs, does not guarantee reliable frequency response in certain scenarios after contingencies. To achieve minimum system cost and good dynamic frequency behaviour, real systems should move to using economic dispatch models that include frequency-related constraints.

Keywords: RES providing reserve; Unit commitment; Island Power System; Deloading of Wind Energy; Down-reserve provision; Up-reserve provision; Frequency regulation

1. Introduction

Island power systems face two major problems: a small size and a weak or non-existent interconnection with other power systems, which makes them more vulnerable to frequency disturbances and leads to higher system operation costs than in large interconnected systems.

The small size of these systems has an impact on their frequency stability, which depends primarily on the contingency that takes place, the total inertia of the system and the control capacity. There are fewer generating units connected to the grid, so each of them covers a high percentage of the total demand and the inertia of the system is low. The outage of one of the units can cause a rapid drop in frequency and lead to load shedding if the frequency protections do not act in time. For this reason, the reserve requirements are very demanding in relation to the size of each unit.

In addition, island power systems do not benefit from the economy of scale present in generation. For safety reasons, the installed capacity per unit is limited, small and generally less efficient. The generation mix of these electricity systems is based on gas, fuel oil and diesel, whose operating costs are higher than those of other conventional sources, since the efficiency of these technologies is lower.

The current operator's practice does not allow renewable generation and in particular wind generation to provide reserve in the system, so there are thermal units that must be permanently connected to the grid just to comply with the reserve requirements established by the Spanish regulation. If they were able to participate in the reserve, the generation scenario would change, reducing thermal generation and consequently the operating costs. In order to provide reserve and frequency regulation, wind turbines must work below their maximum generation point by considering a deloading factor.

This Final Degree Project has as its main goal to analyse the impacts on the dynamic frequency response in the system of considering a fixed and a variable wind deloading factor, as well as its relation with the corresponding economic impacts. For this purpose, a weekly economic dispatch model and a dynamic frequency model will be used, and different cases and scenarios of wind energy penetration will be analysed. Its achievement will contribute to Sustainable Development Goals 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities) and 13 (Climate Action).

2. Methodology

The methodology, shown in Figure 1, simulates the economic operation of the system by means of an hourly unit commitment model on a weekly basis, which determines the hourly generation set point as well as the hourly start-up and shut-down decisions. The inputs of this model include the total weekly demand per hour, the renewable generation forecasted and the list of synchronous generators with their data sheet. Then, the results obtained are used as the input of the system frequency dynamics model, where the outage of every online generator (including wind) in every hour of the week is simulated to observe the frequency response of the system.

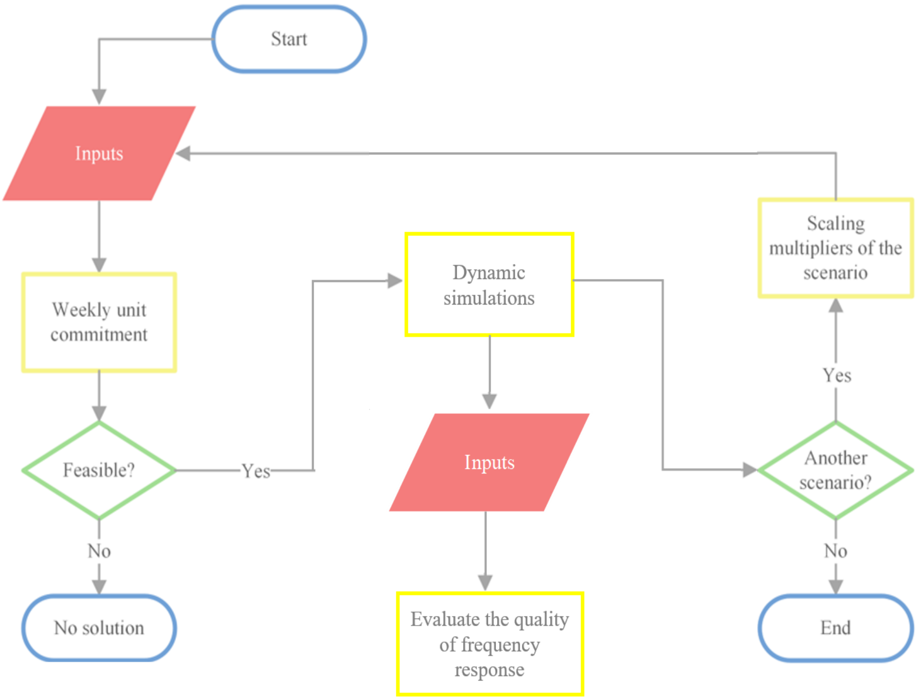

Figure 1. Flowchart of the methodology

The analysis will be performed for the islands of La Palma (small size) and Tenerife (medium size) for a representative week of each season of the years 2020, 2025 and 2030, whose demand profiles will be scaled up and for 4 wind generation scenarios. Scenario I contemplates the current amount of installed wind capacity. For scenarios II to IV, the current amount is multiplied by 2, 5 and 10, respectively. For each scenario, the following cases of reserve provision by wind generation are defined:

- Case A: all the necessary reserve and inertia must be provided by the thermal units and the wind discharge factor is set to zero.
- Case B: a fixed wind energy deloading factor of 10% of the available power are considered. Emulation of inertia is also included.
- Case C: a variable wind energy deloading factor of between 0 and 15% of the available power are considered. The optimum value will be decided by the economic dispatch. Emulation of inertia is also included.

In addition, to analyse the frequency response, all simulations will be performed with and without the current load shedding scheme activated.

3. Results

3.1. La Palma

The seasonal average number of severe cases, the daily operation cost and the expected cost for UFLS in one year are represented in Figure 2.

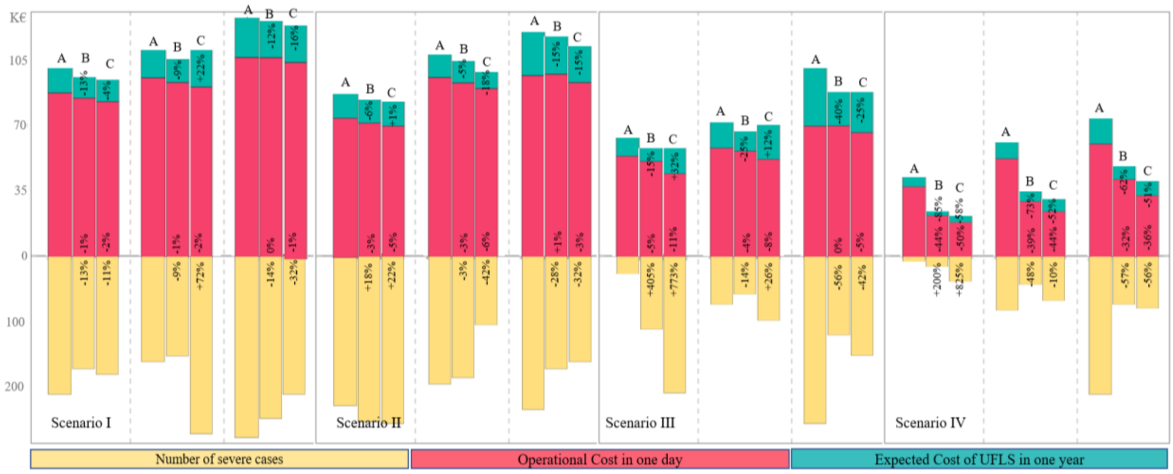

Figure 2. The average technical and economic results of 4 seasons for La Palma island

Results show that the total operation cost is lower when a deloading factor is considered. Since in the base case A there are thermal units that must be permanently connected to the grid only to cover reserve requirements, part of the total available renewable generation ends up being spilled. In addition, in the cases with deloading, the number of connected units is lower since part of the thermal generation can be disconnected.

However, considering a deloading factor only improves the frequency response if the demand is high (years 2025 and 2030), since more units are connected and the loss of one of them has less impact. With low demand and being a small island, there are very few generators connected, so the loss of one of them has a large impact on the frequency response of the system. It is worth mentioning that comparing different cases implies comparing different economic dispatches, since the connected units vary from one case to another.

Furthermore, the results show that the economically optimal factor (case C) is not necessarily optimal for the improvement of the frequency response. In fact, case C does not always improve system frequency response and has no correlation with demand and wind penetration. It only deloads wind generation in the hours when not enough thermal generation reserve is scheduled, which means that less deloading is scheduled compared to case B, to serve as a power reserve. When a contingency occurs, it has less power to serve as reserve and may result in a worse frequency response.

By activating the current underfrequency load shedding schemes, the better the frequency response of the system, the lower the load shedding is. For the same demand in the cases with deloading, the total shed power in all contingencies is reduced as the wind penetration increases. The reason is that, by providing frequency regulation, the dynamic response of the system improves and, therefore, less load has to be de-shed.

3.2. Tenerife

The seasonal average number of severe cases, the daily operation cost and the expected cost for UFLS in one year are represented in Figure 3.

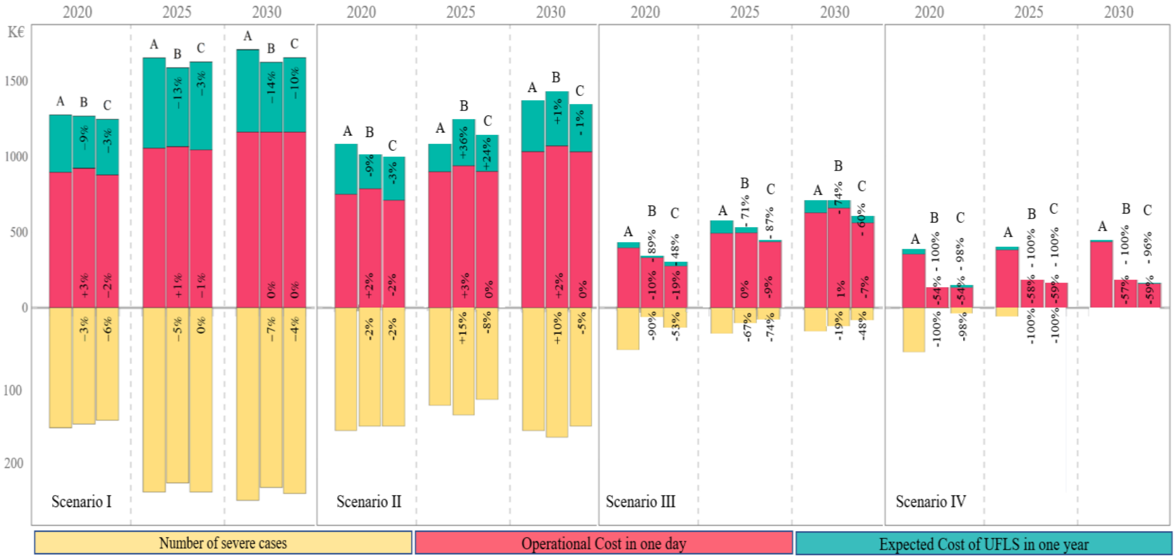

Figure. 3. The average technical and economic results of 4 seasons for Tenerife island

Results show that deloading always improves the frequency response, but again, the economically optimal deloading factor is not necessarily the one that gives the best frequency response.

In case B, a constant deloading factor of 10% is considered. From their results it can be observed that in some hours deloading is unnecessary, since the frequency response worsens with respect to case A. The reason is because two different economic dispatches are being compared. Having a constant deloading factor is also not advisable from an economic point of view when wind penetration is low. However, in those specific cases, having a variable deloading factor (case C) does improve the response and optimizes the total cost.

Results also show that for future wind penetration scenarios the frequency response of the system always improves. If wind power also participates in the frequency regulation, the frequency response is very good, and no severe cases occur. This means that no load shedding is needed, and the grid becomes safer and more efficient.

In general, the total cost (operational and expected from load shedding) is higher in the case without load shedding capability. Case C provides the best economic results, as it considers the economically optimal unloading factor. This is especially noticeable in the high wind penetration scenarios (III and IV), where a large cost reduction occurs, as well as an optimal frequency response. It can therefore be seen that a higher number of severe cases results in a higher total cost.

If the simulations are performed with the current load shedding scheme, for the same demand and high wind penetration, the total shed power for all contingencies remains constant in all cases. This occurs even in case A, where an increase in this value would have been expected. The reason is that, although wind turbines do not provide frequency regulation, fewer units are connected online, there are fewer contingencies, and less load must be shed. In addition, as wind power increases, the load shed is reduced due to an improvement in frequency response. Consequently, in cases B and C the deloading is less than in the base case. In general, the worse the frequency response, the greater the amount of load that will have to be shed in order not to violate the frequency limits imposed by Spanish regulations. As the frequency response improves, the expected cost of underfrequency load shedding decreases.

4. Conclusions

This work shows that, under the current practice of the system operators and, in order to promote the implementation of renewable energies in the future, it is essential to have a fixed deloading factor of wind energy and not a variable one obtained by the economic dispatch, since the latter does not take into account the dynamic behavior of the system.

The results obtained show that the deloading factor is always beneficial, both from the technical and economic point of view when the size of the island is medium, as is the case of Tenerife. When wind penetration is high, the frequency response improves, the system becomes more secure and, in some hours, load shedding is not necessary. As a result, the total expected cost due to possible load shedding is reduced, which is an additional economic benefit. It is then concluded that the benefits of providing reserve with renewables on medium-sized islands can appear immediately if the considered load shedding factor is adequate.

On the other hand, on small islands, providing frequency regulation by wind turbines only improves the frequency response when system demand is high. Given their smaller size, each generating unit covers a high percentage of the total demand and, as a result, the outage of one of them has a considerable impact on the frequency response of the entire system. Therefore, allowing wind generators to provide frequency regulation is not urgent in terms of improving frequency response, as the benefits will appear when demand increases in the coming years.

Furthermore, it is shown that deloading wind power is not advisable in low wind penetration scenarios. However, considering future scenarios in which system demand will increase and given the tendency of system operators to add more renewable generation, the results suggest that using the appropriate deloading factor is advisable to improve the overall system frequency response and reduce total operating costs. It is therefore interesting to consider economic dispatch models that include frequency-related constraints to optimize both the costs and the dynamic response of the system.

Future work will address the analysis of the frequency response under future optimal deloading schemes. The implementation of frequency constraints in economic dispatches will also be analysed in order to find the variable deloading factor that achieves optimal results in both frequency response and total system costs.

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1. INTRODUCTION

This section introduces the problematics that island power systems face and explains the main motivations of the project.

1.1. ISLAND POWER SYSTEMS

Island power systems have a small size and a weak or even non-existent electricity interconnection to other power systems. The lack of both technical and economic support from neighbouring systems as well as their remoteness and small area makes them more vulnerable to frequency disturbances and causes higher system operating costs than in large interconnected systems [1]. As Figure 1 illustrates, there exist currently more than 50 thousand islanded power systems in the world [2], and the number of islanded power systems is expected to keep increasing in the up-coming years [3].

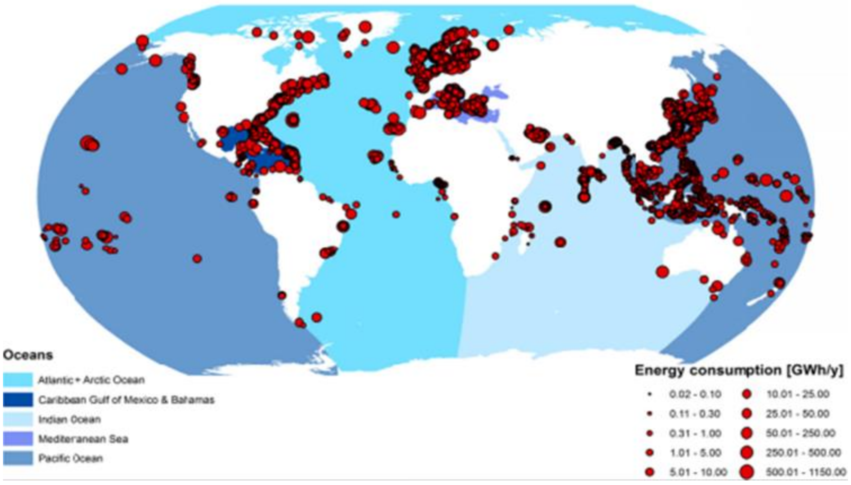

Fig. 1. Island power systems in the world. Source: [2].

The geographic isolation of island power systems affects them in two main ways. On the one hand, the small size of these systems has an impact on their stability and, in particular, on their frequency stability. Frequency stability depends fundamentally on the disturbance that takes place, on the inertia of the system and on its control capacity. The smaller size implies that there are fewer generating units connected to the net, which means that the total inertia of the system is lower. In addition, the generation of each unit represents a high percentage of the total demand [4]. The outage of one online unit can result in a rapid drop in the frequency, causing a blackout if the frequency protections do not act in time. Because of these reasons, island power systems are more prone to suffer from frequency instability than larger interconnected systems such as the Eastern and Western systems of Canada and the United States of America or the Continental European system.

On the other hand, island power systems do not benefit from the economy of scale present in generation. For safety reasons, the installed capacity per group is limited, small and generally less efficient. The generation mix of these power systems is based on gas oil, fuel oil and diesel, whose operational costs are higher than other conventional sources since the efficiencies in the power generation technologies are lower. Additionally, due to the high percentage of the total demand that each generating unit covers, the spinning reserve requirements are more demanding in relation to the size of each of the generating units. This, together with the logistics costs of raw materials, increase the total operating cost of the system.

1.2. FREQUENCY REQUIREMENTS OF SPANISH ISOLATED POWER SYSTEMS

This section provides a short review of the frequency requirements of Spanish isolated power systems, which include their economic regulation, reserve, ranges of frequency and underfrequency load shedding (UFLS) schemes.

The Spanish isolated power systems, also known as SEIE (Sistemas Eléctricos Insulares y Extrapeninsulares), are the power systems of the Canary Islands, Balearic Islands, and the Spanish towns in North Africa: Ceuta and Melilla. These systems have very different sizes. The largest power system is Balearic system, which has a peak demand larger than 1100 MW and the smallest power system is in the island of El Hierro, which has a peak demand of approximately 7 MW.

1.2.1. ECONOMIC REGULATION

The economic operation of island power systems is different from the mainland. They can work either under a market driven scheme or under a classical centralized scheme. Spanish isolated power systems are operated under a classical centralized scheme.

In this kind of operation, all the generating units are programmed following an economic dispatch that prioritises the security of supply criteria over the total costs. In particular, the generation of each unit is determined over different time horizons: weekly, daily, intraday and real-time. The weekly generation is programmed by three unit commitment (UC) models: the first one considers only the economic optimization with standardized variable operation costs, the second one also considers the security requirements, and the last one includes technical restrictions and additional constraints that the transmission grid imposes, re-scheduling generating units if needed. The determination of a daily generation is similar to the determination of a weekly generation.

In [5], generators in Spanish islands power systems are divided into two categories:

- Category A: it includes hydro (excluding the run of rivers), thermal generators and cogeneration power plants with total net power greater than 15 MW. Generators of this category that have been included in the additional remuneration scheme (régimen retributivo adicional), are remunerated according to fixed and variable generation costs, which include emission rates that depend on the generation technology, the secondary reserve costs, the start-up costs and the fuel variable costs among others.

This remuneration scheme repays investments and operation expenditures. Generators of category A that are not recognised in the additional remuneration scheme receive a payment according to energy selling price of each hour and the total energy produced.

- Category B: it refers to all renewable energies and cogeneration power plants with a net power equal or lower than 15 MW. Generators of this category are remunerated according to the hourly energy selling price and the energy produced plus a specific remuneration and, if it is the case, a payment for their contribution to ancillary services. The energy selling price for each hour depends on daily or intraday market price of the peninsular electrical system, weighted by the relation between the demand of each hour and the average daily demand of the island power system of interest.

Considering that the security of supply requirements is maintained, renewable sources and high efficiency cogenerators of both categories A and B always have priority of dispatch when the economic conditions are the same.

1.2.2. RESERVE REQUIREMENT

The technical regulatory framework of the Spanish island power systems is established in a set of operational procedures [5]. Among others, the operation procedure number 1 (stated in section 8.1) describes the spinning up and down reserve requirements in the isolated Spanish power systems. In particular, it highlights the following requirements:

- The primary up reserve must be at least 50% of the maximum power of any generator set in each hour. In a combined cycle unit, each power plant is considered as an independent unit.
- The sum of the up primary reserve and the up secondary reserve must be at least equal to the largest online unit, to the increase in demand foreseen for the following hour, to the power contributed by the interconnections following the N-1 criteria and to the most probable loss of wind power. However, the percentage of renewable generation to be considered adequate is not specified.

- The secondary down reserve is established between 40 and 100% of the up-spinning reserve. These values could be modified depending on the future evolution of the spanish isolated power systems.

The operational procedure also states that when the outage of a large unit takes place, primary frequency control uses both primary and secondary up reserves.

1.2.3. FREQUENCY RANGES

In [6], technical requirements of frequency stability for Spanish isolated power systems are defined. A generating unit must be able to remain connected during a minimum period of time to the grid and work at the frequency values showed in Table I. Additionally, the constant rate of change of frequency (RoCoF) that an online unit must stand is 2 Hz/s, measured over a moving time window of 750 ms.

Frequency range	Period of time working
47,0 Hz – 47,5 Hz	3 seconds
47,5 Hz – 48,0 Hz	1 hour
48,0 Hz – 51,0 Hz	Unlimited
51,0 Hz – 52,0 Hz	1hour

Table I. Frequency range and minimum periods of time during which a generating unit must remain connected.

1.2.4. UFLS SCHEMES

Underfrequency load-shedding schemes are fundamental in power systems to avoid frequency instability. In island power systems where every power imbalance has a considerable impact on the frequency dynamics, UFLS protection is especially important.

UFLS schemes are activated when the frequency threshold specified is reached. Red Eléctrica de España (REE) grid codes for isolated power systems requests to use RoCoF steps with frequency thresholds of 47-50Hz [1]. The efficiency of the UFLS depends on the design of its parameters, which are based on the characteristics and operation of the power system, and its main objective is to minimize the total amount of load shedding. There are different criteria for the design of an UFLS scheme, such as the minimum quantity of load shedding, the frequency limits shown in 1.2.3, or the minimization of the frequency deviation. To define its parameters, different contingencies are studied. In island power systems, only generators outages are normally considered as contingency scenarios [7].

In [8], UFLS are grouped into manual schemes (used for the restoration of frequency) and automatic schemes (used to stop the frequency decay and to bring the frequency back to an acceptable value). The latest can be grouped in advanced UFLS (that comprise adaptive and centralized schemes) and conventional UFLS, which include static schemes that only use underfrequency relays and semi-adaptive schemes (which employ the constant rate of change of frequency delays to compute the amount of load to be shed) [1].

1.3. MOTIVATION OF THE PROJECT

In the recent years, the availability of renewable energy sources (RES) has increased, offering an interesting solution to decrease the current dependency on fossil fuels and to increase island sustainability. However, due to their lack of inertia, their unpredictable availability and, in order to guarantee the stability of the system, these sources of energy are often curtailed whenever over-generation is about to be reached.

The question of whether spinning reserve should still be fully provided by thermal generators only or whether non-synchronous renewable sources should contribute as well has arisen in the recent years. Nowadays, renewable generation does not participate in the up and down spinning reserve of the system. As a result, there are conventional thermal units that must be permanently connected to the grid working between their minimum and maximum power values in order to fulfil the reserve requirements imposed by the Spanish regulation. If renewable energy sources were able to participate in the reserve of the system, the generation scenario for the same demand would change as a result of a higher share of RES, and operation costs would be reduced. To provide reserve, renewable groups must operate below their maximum power point tracking (MPPT), which depends on parameters such as the season of the year or the time of the day. Figure 2 illustrates how, for a specific amount of wind, wind turbine generators (WTGs) can participate in the primary frequency regulation of the system and provide reserve when they operate on the deloading power curves instead of on the MPPT curve. In the deloading power curve they leave a power margin that can be used as reserve.

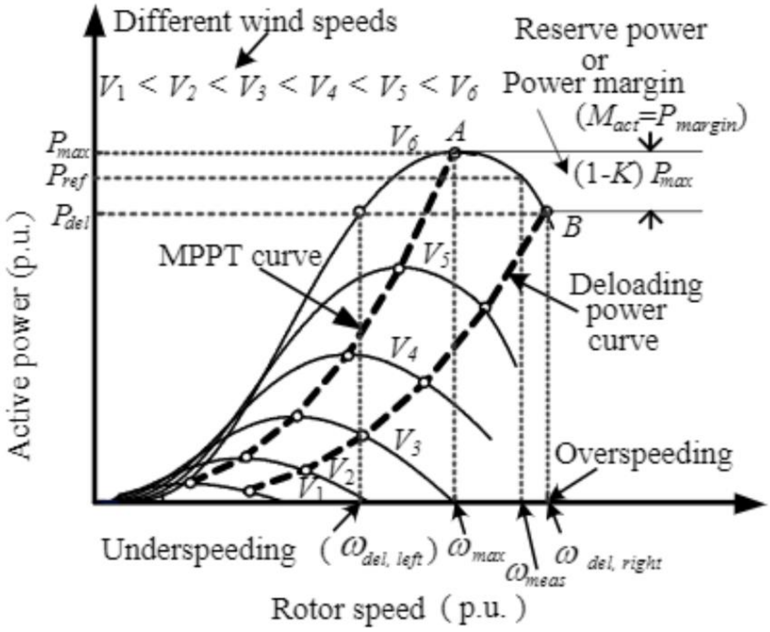

Fig. 2. MPP and deloading curve. Source: [9].

Figure 3 provides a simple and hypothetical example to illustrate the main idea and economic benefits of RES providing spinning reserves in the system [10]. A certain demand at a particular instant is covered by two thermal units G1 and G2, and two wind generators W1 and W2. All the units have the same size in terms of maximum generation limit at that instant. In Figure 3 (a), the demand, as well as the spinning reserves, is fully covered by the thermal units G1 and G2. Both operate at the same power level to cover their possible individual outages. In Figure 3 (b), the demand is mostly covered by the wind farm W1, but unit G1 is also connected at its minimum power generation level, leaving room to provide the required reserve established by the Spanish regulation. Lastly, in figure 3 (c), the demand, as well as the spinning reserves, are entirely covered by the wind farms W1 and W2.

This example shows the positive impacts on the system when RES are able to provide reserves. In an ideal scenario, RES is able to cover both the reserve and the demand of the system, enabling the disconnection of thermal units.

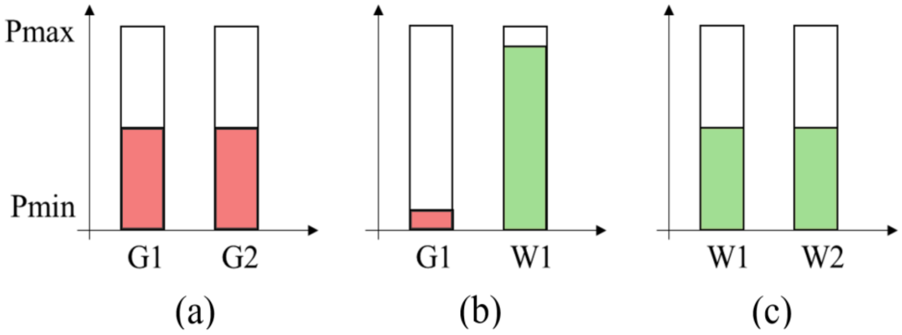

Fig. 3. Illustration of the benefits of providing spinning reserves by RES. Source: [10].

(a) Demand and total reserve covered by G1 and G2
(b) Demand covered by W1 and reserve covered by G1
(c) Demand and total reserve by W1 and W2.

With the goal of analysing the technical and economic impacts of RES providing reserve and frequency regulation in extra-peninsular power systems, this work has chosen the islands of Tenerife (medium size) and La Palma (small size), belonging to the Canary Islands, as they are representative for the Spanish isolated power systems. Further, given than these two islands have been identified by clustering techniques as two of the five prototypes of islands power systems that exist worldwide [11], the results shown in this work can be extrapolated to other islands power systems.

This work continues the line of research started in [10], where the positive economic impacts of RES providing spinning reserve has been proved. It considers the same scenarios and cases and provides a wider perspective of the topic by analysing it from a technical point of view.

According to the Canary Islands Energy Yearbook of 2018 [12], there was a total annual production of more than 9280 GWh, consisted of around 10% renewable generation, nearly 90% thermal generation and less than 0.01% refinery and cogeneration in 2018. Only in year 2018, an amount of almost 1820 kilotons of fuel (including diesel oil and fuel oil and gasoil) was imported to Canary Islands, to cover the electricity demand. In order to reduce this high consumption of fuel, 200% of the total amount of renewable resources is planned to be added by 2025, and a 400% by 2030.

Further, in Spain the National Integrated Energy and Climate Plan proposes as one of its main targets for 2030 a reduction in the total gas emissions of 21% with respect to year 1990 values, and a coverage of total demand by RES of 42%. This plan was made regarding the 2015 Paris Agreement, in which the member countries committed to reduce greenhouse gas emissions by 40% with respect to 1990 levels [13]. This work mainly contributes with Sustainable Development Goal number 7 (Affordable and clean Energy), with number 11 (Sustainable cities and communities) and number 13 (Climate Action), as shown in Annex D.

In this context, the main motivation of this work is to contribute to the achievement of these Sustainable Development Goals, considering different penetration scenarios of generation by non-synchronous renewable sources and always guaranteeing the continuity of the electric service following stability, security, and quality of supply criteria. This will lead to a reduction in thermal generation, as well as in total operating costs. In addition, with the achievement of this project, possible load shedding caused by generator outages will be reduced and island power systems will become more efficient and secure.

2. STATE OF THE ART

The improvements in renewable generation technologies together with a growing concern about the environmental impact of thermal generation and a boost of the global energy demand, are leading to an increasing interest in investigating new initiatives to evolve towards electric power systems that are more dependent on renewable energies, with wind power being the preferred option in the case of island systems [14]. In fact, reducing the energy dependency on fossil fuels is urgent, since the oil price has grown with an annual average rate of 5% over the past two decades and it is expected to keep growing with the annual rate of 3% in the next 20 years [2].

Renewable energy sources (RES) offer an attractive solution not only to minimize the use of fossil fuels and increase island sustainability [15], but also to achieve cost-optimal electricity systems [16]. In [17], the possibility of achieving 100% renewable generation in Canary Islands before 2050 is investigated and in some islands it has already been achieved [18]. In order to promote the deployment of RES in island power grids, the International Renewable Energy Agency (IRENA) launched the Global Renewable Energy Island Network (GREIN), a platform whose goal is to exchange ideas and share best practices about the development of islands’ renewable energy provision.

However, the increasing penetration of RES without providing spinning reserve and inertia can negatively affect the frequency stability of island power systems even more ([19],[20]), by reducing control capacity of the system and the total inertia. As this form of energy is decoupled from the system by convertors, it does not provide spinning reserve. As a result, thermal generators must be connected above minimum power to provide the required amount of down reserve and same or different thermal units must function below their maximum power to provide the required amount of up reserve in some periods. If RES provided reserve, the commitment status of units could change, and the total operation costs could be reduced.

Spinning reserves in power systems are characterised by their fast start capability and denote the sufficient power and energy reserves to contribute to frequency stability. They are a key aspect in the stability of the isolated system frequency. Therefore it is essential to adapt the size optimally so that they are sufficient to cover both emergency and non-emergency situations [21]. Non-emergency conditions include the wind and solar generation forecast error or the total demand forecast error. Emergency incidents include for instance the outage of generation units and transmission lines [22].

Common practice among island system operators is to establish a value of minimum spinning reserve requirement to be able to cover the loss of the largest on-line generating unit, expected RES variations and loss of interconnections, as explained in 1.2.2. Under this common practice, thermal generators are the providers of spinning reserve and inertia, functioning below thir maximum power to provide the required amount of up reserve in some periods, and thus increasing system operation cost. All available RES generation is directly injected to the power system without providing spinning reserve, substituting thermal generation. In addition, non-synchronous RES are unable to provide inertia by default, as they are connected to the grid through a power electronic converter that decouples the wind turbine's inertia [23]. Consequently, a higher RES penetration results in a higher constant rate of change of frequency (RoCoF), leading to frequency stability challenges. Current frequency protections shed certain amounts of loads whenever the frequency or the frequency derivative exceeds certain thresholds ([4], [7], and [24]). Advanced adaptive protections are also being developed [25].

The injection of an unknown amount of renewable generation into the power system results in a great uncertainty for the system operation. Consequently, a large spinning reserve is needed in the system to ensure the balance between the real time demand and the forecasted power. The provision of reserve margins to hedge against the uncertainty and variability that wind power generation introduces in the electrical grid has been studied in references [26] and [27]. The impact that forecasting the amount of wind generation has on reserve requirements has been analysed in [28]. Nevertheless, nowadays wind generators do not provide spinning reserves in Spanish island systems, as they work in the maximum power point tracking (MPPT) defined by the rotor speed of the turbine. Hence, this non-synchronous generation is often curtailed to ensure frequency stability in the system.

Technical developments enable RES to provide both reserve and inertia emulation. To be able to provide frequency regulation, wind turbines must have frequency control capabilities and be able to provide power reserves [9]. In [29], various reserve allocation methods are compared and a practice to assess immediate wind primary reserve is presented. Reference [30] has tested various control strategies of active power to investigate their effectiveness in times of high wind injection. It concludes that inertial and power frequency response controllers can be implemented on wind turbine generators and enhance the overall frequency response of the system. In [31], an aggregated frequency response model for wind generators is presented, considering the different operational modes of wind power turbines. In [32], a stochastic unit commitment formulation that evaluates the advantages of synthetic inertia and primary frequency response provision from WTGs in Great Britain power system is developed, and concludes that the total operation costs of the system can be mitigated. Reference [33] analyses different inertia and frequency regulation approaches for RES, which include inertia emulation, fast power reserve, droop techniques and deloading techniques with over speed control and pitch angle control which allows RES to keep a certain amount of up spinning reserve.

Among all of these techniques, deloading is the highest reliable one, brings more economic and technical benefits and provides a better overall frequency response [34] even though increasing the pitch dynamics may increase the maintenance cost due to possible mechanical damages.

Although deloading available power enables WTGs to participate in the frequency regulation of the system, it contradicts with the principle of working in the optimal power curve, which is extracted from the look-up table that is generated using wind turbine aerodynamic equation, acquiring the highest possible amount of power from wind source [35]. Wind power are technically able to provide reserves by working below their MPPT [36]. This can be achieved by appropriately adjusting rotor speed. Typically, deloading rate is less than 20% of the available wind power, depending on the circumstances [37]. An complete review on deloading techniques of wind turbines in power systems is presented in [27], and different control modes are compared. In [38], the authors highlight the lack of accuracy of current linear deloading techniques employed, and argue that the nonlinearity between the rotor speed and the output power during the deloading practice must be taken into consideration. Then they propose a nonlinear formulation to enhance stability and frequency regulation participation of wind turbines in micro grids. A stable operation of wind turbine generators is introduced in [9], which guarantees the optimum contribution of each wind turbine with the goal of providing a better frequency response of the system by combining dynamic deloading and droop operation. The authors employ a fuzzy control scheme that adjusts the amount of deloading by sensing the frequency deviations. They recommend the combination of fuzzy-based control and a variable droop and state that because of the uncertainty of wind, to use a controller based on the wind’s measurement might not be precise enough.

3. DEFINITION OF THE WORK

3.1. OBJECTIVES

The main objective of this Final Degree Project is to evaluate the impact of providing spinning reserves and frequency regulation by renewable energy sources and, in particular, by wind turbines generators in isolated power systems, aiming to increase their penetration in island power systems worldwide. Authors in [10] have proven the positive economic impacts of RES providing up and down spinning reserves in the system. The focus of this work is to provide a wider analysis of this topic, focusing on the technical improvements in the overall frequency response following stability and security of the supply criteria. Taking the optimal UC generation scenarios obtained in [10], this final degree project performs all dynamic simulations to thermal and wind outages, measuring the frequency response by a set of key performance indicators (KPIs), such as the frequency nadir or the amount of UFLS. The dynamic performance is also estimated in terms of load shedding cost computed taking into account the forced outage rate of generators. Results will show that for high RES penetration scenarios, the inclusion of a fixed deloading ratio so that RES provide both inertia and reserve, it is possible to improve both total system operational costs and the overall frequency response quality which translates in a lower UFLS cost.

A second objective of this paper is to evaluate when the common practice by system operators of establishing a value of minimum spinning reserve requirement is adequate in real power systems to foster the deployment of RES in future demand scenarios. This common practice neglects the dynamic features (such as the speed or inertia) of the units providing reserve, and thus can lead to increased underfrequency load shedding under contingencies. Results will show that a variable deloading factor worsens the overall dynamic behaviour of certain scenarios with respect to a fixed deloading factor because it is determined by a UC neglecting frequency behaviour. In order to capture both the minimum system cost and best frequency dynamic behaviour, real systems should move to the use of unit commitment models that include frequency related constraints.

Statistics show that the current amount of available renewable generation is not sufficient to cover the future energy necessities of the world’s increasing population. As a result, new mechanisms are needed to guarantee a higher RES penetration. This work analysis one possible mechanism that can lead to achieve a greater supply of the demand by non-synchronous renewable energies in islanded systems, optimizing the operation costs and increasing sustainability by reducing the environmental impact of conventional generation technologies.

The ultimate goal of this project is to replace thermal generation units with renewables and to use them in a smarter way, which will improve the efficiency of the electricity system. This will contribute to the sustainability objectives established for 2030 that aim to cover the total demand of the system by renewables and to reduce the total emission of greenhouse gases.

3.2. METHODOLOGY

This section presents the methodology to assess the technical and economic impacts of providing frequency regulation and spinning reserves by wind turbines generators in island power systems. The assessment simulates the economic operation by means of an hourly unit commitment (UC) on a weekly basis, which determines the hourly generation set point as well as the hourly start-up and shut-down decisions [10]. Then, these results are used as the input of the system frequency dynamics (SFD) model. In this model the outage of every online generator (including wind) in every hour of the week is simulated to observe the frequency response of the system after each contingency.

The methodology simulates of the economic operation and the dynamic response of two Spanish islands (Tenerife and La Palma) under different demand profiles, wind penetration scenarios and cases with different approaches of providing reserve. For a given weekly demand profile, the corresponding current wind penetration profiles are scaled up according to an estimated future installed capacity. This method is an approximation for future profiles under higher wind penetration scenarios, given that the current installed wind generation and wind spillage are low. The different cases and scenarios considered are introduced in section 4.

The simulation of the economic operation, considering whether the wind turbines are controllable and able to provide reserves and frequency regulation or not is performed for each of the considered cases of study. For the feasible simulations, the outputs of the unit commitment model including binary variables of the generators (whether they are online or not) and hourly scheduled power of units are used as the inputs of the dynamic simulation, where the frequency response of the system after every single thermal or wind online generator outage is performed. Key performance indicators will be determined after each simulation to evaluate the quality of the frequency response. For each of the islands, the simulations are run both without considering under-frequency load shedding (UFLS) schemes and under the current existing UFLS schemes.

Figure 4 illustrates the flowchart of the methodology used. The inputs of the weekly UC model include the weekly demand per hour, the renewable generation forecasted, the list of synchronous generators and their data sheet (which includes their gain, inertia, power limits and control parameters) for both islands and each sample week under study.

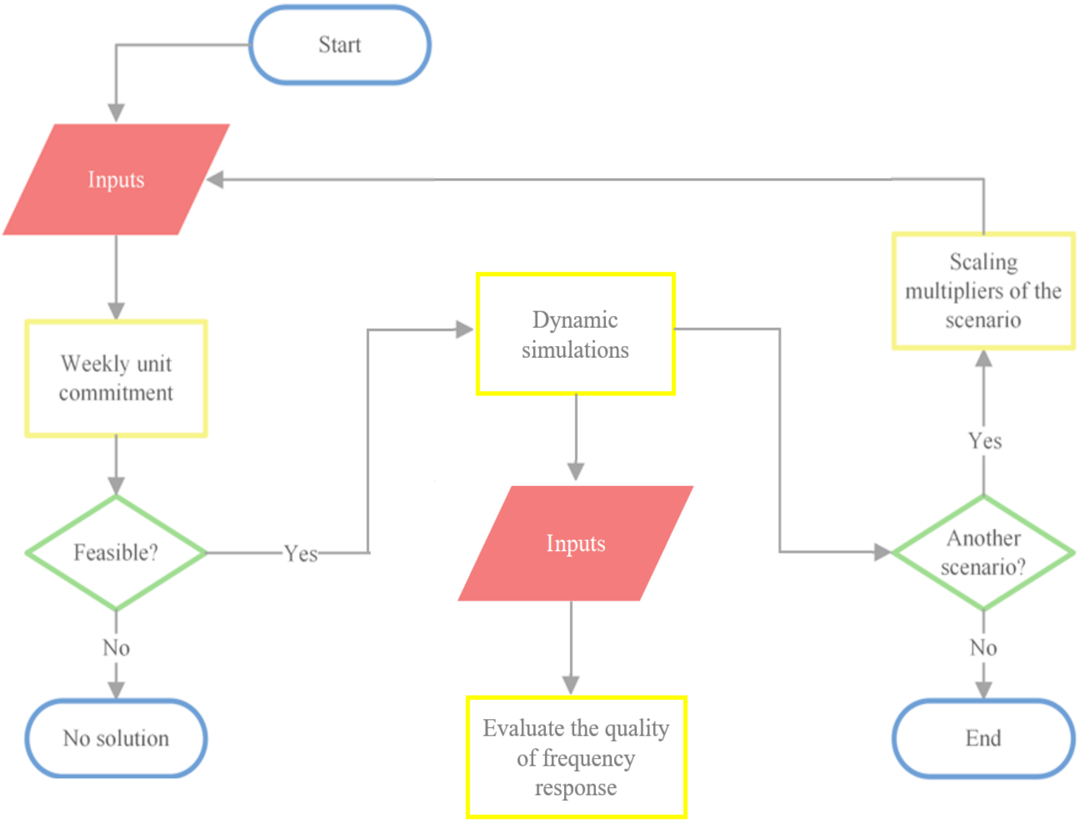

Fig. 4. Flowchart of the methodology

3.3. MATHEMATICAL FORMULATION OF THE ECONOMIC DISPATCH MODEL

This subsection presents the unit commitment model used in this work. First, an overview of the proposed model is given. Second, the nomenclature used is explained, including indexes and sets, parameters, and continuous and binary variables. Finally, the objective function, binary logic and constraints are detailed.

3.3.1. LINEAR OPTIMIZATION MODEL

Spanish island power systems operate under a centralized scheme that follows an economic dispatch whose goal is to cover the total demand of the system and, at the same time, minimize the total costs. Different unit commitment models have been proposed in the literature using Lagrangian relaxation, dynamic programming, exhaustive enumeration, interior point methods and mixed-linear integer programming (MILP) among others. This work has used the latest method, following the UC model described in [1]. Constraints related to spinning reserve and frequency regulation provision by renewable energy sources have been added to the base model, as explained in the following subsections.

The UC is formulated as a minimization problem where generation set points and start-up and shut-down decisions are such that the total weekly operation cost is minimized by considering technical constraints. The model is developed in the modelling language General Algebraic Modeling Systems (GAMS) and the commercial solver used is CPLEX. The nomenclature, objective function and constraints are shown next.

3.3.2. NOMENCLATURE

This subsection details the nomenclature used in the unit commitment model, which is classified in indexes, sets and parameters (represented in uppercase letters), and continuous and binary variables (represented in lowercase letters).

- ***Indexes and Sets***

Symbol	**Description**
$i \in I$	Thermal units, from *i* to *I*
$res \in RES$	Renewable sources, from *res* to *RES*
$dw \in DW$	Deloading wind units, from *dw* to *DW*

$cres \in CRES$	Controllable renewable sources providing down reserve, from *cres* to *CRES*
$t \in \tau$	Hourly periods, in time horizon τ

- ***Parameters***

Symbol	**Description**
C_i^{fix}	No load cost, [€]
C_i^{lin}	Linear coefficient of the cost variable, [€/MWh]
C_i^{qua}	Quadratic coefficient of the cost variable, [€/MW2h]
$C_i^{start-up}$	Start-up cost of unit i, [€]
$C_i^{shut-down}$	Shut-down cost of unit i, [€]
$\overline{P_i}$	Maximum power of unit i, [MW]
$\underline{P_i}$	Minimum power of unit i, [MW]
$\overline{R_i}$	Ramp-up rate of unit i, [MW/h]
$\underline{R_i}$	Ramp-down rate of unit i, [MW/h]
$D(t)$	Total power demand in hour t, [MW]
$P_{res}(t)$	Forecasted renewable generation for time t, [MW]
$DF(t)$	Deloading factor at time t, [-]
k_{RV}	Expected renewable output variations, [-]
k_{DR}	Down reserve requirement coefficient, [-]
$P_{cres}(t)$	Forecasted power of controllable renewable source cres at time t, [MW]

- ***Continuous variables***

Symbol	**Description**
$p_i(t)$	Scheduled power generation of unit *i* at time *t*, [MW]
$p_{dw}^{deloaded}(t)$	Deloaded power from wind unit *dw*, [MW]
$p_{res}^{spilled}(t)$	Spilled power of renewable source *res*, [MW]
$URR(t)$	Up reserve requirement at time *t*, [MW]
$DRR(t)$	Down reserve requirement at time *t*, [MW]
$r_i^{up}(t)$	Up reserve provided by unit *i* at time *t*, [MW]
$r_i^{down}(t)$	Down reserve provided by unit *i* at time *t*, [MW]

- ***Binary variables***

Symbol	**Description**
$x_i(t)$	On/off status of unit *i* at hour *t*
$y_i(t)$	Start-up status of unit *i* at hour *t*
$z_i(t)$	Shut-down status of unit *i* at hour *t*

3.3.3. OBJECTIVE FUNCTION

As stated in [1], the main objective of the UC model is to minimize the total thermal operation costs, by finding the optimum start-up decisions of thermal units and their hourly generation. The formulation of the objective function is:

$$\min \sum_{t\in\tau} \sum_{i\in I} \Big[\big(\mathrm{C_i^{fix}} \cdot \mathrm{x_i(t)} + \mathrm{C_i^{lin}} \cdot \mathrm{p_i(t)} + \mathrm{C_i^{qua}} \cdot \mathrm{p_i^2(t)} + \mathrm{C_i^{start-up}} \cdot \mathrm{y_i(t)} + \mathrm{C_i^{shut-down}} \cdot \mathrm{z_i(t)} \big) \Big] \tag{1}$$

3.3.4. BINARY LOGIC

Binary logic regarding the on/off status of thermal units and their start-up and shut-down decisions is defined in the following set of equations:

$$x_i(t) - x_i(t-1) = y_i(t) - z_i(t), \qquad t \in \tau \tag{2}$$

$$y_i(t) - z_i(t) \leq 1, \qquad t \in \tau \tag{3}$$

3.3.5. CONSTRAINTS

- ***Balance***

Concerning the power balance of the island in each hour, the total power generation (thermal units and wind farms) must be equal to the total demand of the system.

$$\sum_{i \in I} p_i(t) + \sum_{res \in RES} P_{res}(t) - \sum_{dw \in DW} p_{dw}^{deloaded}(t) - \sum_{res \in RES} p_{res}^{spilled}(t) = D(t), \quad t \in \tau \tag{4}$$

Where $p_{res}^{spilled}(t)$ is the total amount of spillage that is scheduled for wind energy and $p_{dw}^{deloaded}(t)$ is introduced in the next subsections.

- ***Technical requirements for operation of thermal units***

The thermal technical operation includes ensuring that thermal units operate between their minimum and their maximum limits (5) and imposing the ramp up and down limits (6). Any variation of power between two consecutive hours should not exceed generator’s ramping limitations.

$$\underline{P_i} \cdot x_i(t) \leq p_i(t) \leq \overline{P}_i \cdot x_i(t)\,, \quad \forall i \in I, \forall t \in \tau \tag{5}$$

$$-\underline{R_i} - \overline{P_i}.\, z_i(t) \leq p_i(t) - p_i(t-1) \leq \overline{R_i} + \overline{P_i}.\, y(t), \qquad \forall i \in I, \forall t \in \tau \tag{6}$$

- ***Wind Discharge***

Wind generators can have energy stored as reserve to support the system whenever a contingency occurs only if the turbine functions below the maximum power point tracking (MPPT). In order to do that, it must work with the deloading control mode, where the MPPT is reduced by a deloading factor in the optimization problem. However, the wind turbine should be controllable (receive set point variations). This is, if RES is controlled, it can be reduced by spilling energy with respect to the total available wind generation. Typically, RES generation under current scenarios is only spilled in case of possible issues with respect to system stability (like over-generation).

$$p_{dw}^{deloaded}(t) = P_{dw}(t) \cdot DF(t) \quad \forall t \in \tau, dw \in DW \tag{7}$$

- ***System Reserve Requirements***

The Spanish regulations for island power systems state that up spinning reserve in each hour must be bigger than the maximum possible power generated by the largest operating unit and the expected RES uncertainty, and down spinning reserve in each hour must be greater than the down spinning reserve requirement (k_{DR}) of the up-spinning reserve.

In this work, following the criteria stated in [10], the k_{DR} is set to 50% and the expected renewable output variations ($\mathbf{k_{RV}}$) is set to 30%.

$$\begin{aligned} &URR(t) \\ &= max\left\{\begin{matrix} max\,\{p_i(t), i \in I\}, \\ \left(\sum_{res\in RES}\left(P_{res}(t) - p_{res}^{spilled}(t)\right) - \sum_{dw\in DW} p_{dw}^{deloaded}(t)\right).k_{RV} \end{matrix}\right\} \end{aligned} \tag{8}$$

$$DRR(t) = URR(t).k_{DR}, \quad \forall t \in \tau \tag{9}$$

- ***System Reserve Provision***

The thermal unit must be able to accomplish a positive or negative variation of active power in 15 minutes [39].

The following equations limit the amount of scheduled reserve to the extent that ramp-up and ramp-down rate of the unit allow (as 15 minutes is a quarter of an hour, the ramp-up and ramp-down rates are divided to 4).

$$r_i^{up}(t) \leq \sum\nolimits_{i\in I}\left(\overline{P_i}.\,x_i(t) - p_i(t)\right), \quad \forall t \in \tau \tag{10}$$

$$r_i^{up}(t) \leq \frac{\overline{R_i}}{4}, \quad \forall t \in \tau \tag{11}$$

$$r_i^{down}(t) \leq \sum_{i\in I}\left(p_i(t) - \underline{P_i}.\,x_i(t)\right), \quad \forall t \in \tau \tag{12}$$

$$r_i^{down}(t) \leq \frac{\underline{R_i}}{4}, \quad \forall t \in \tau \tag{13}$$

RES can provide up reserve if they work below the maximum power point tracking (MPPT) and the proper control mechanism is implemented on them. When they have the deloading control activated, wind turbines can participate in the up reserve of the system. Also, they can provide down reserve if they are able to sense the frequency of the system and curtail their generation if the frequency is high.

The following equation guarantees that the total available up spinning reserve (provided both by thermal generators and wind turbines) meets the requirements.

$$\sum_{i\in I} r_i^{up}(t) + \sum_{cw\in CW} p_{cw}^{deloaded} \geq URR(t), \quad \forall t \in \tau \tag{14}$$

The following equation guarantees that the total available down spinning reserve (provided both by thermal generators and wind turbines) meets the requirements.

$$\sum_{i\in I} r_i^{down}(t) + \sum_{cres\in CRES}\left(P_{cres}(t) - P_{cres}^{spilled}(t)\right) - \sum_{dw\in DW} p_{dw}^{deloaded}(t) \geq DRR(t) \qquad \forall t \in \tau \tag{15}$$

3.4. SYSTEM FREQUENCY DYNAMICS MODEL

This subsection presents the nomenclature of the system frequency dynamics (SFD) model, as well as an explanation of the modelling of the system and of the wind generators.

3.4.1. NOMENCLATURE

The system frequency dynamic model is defined with a set of parameters, abbreviated as:

Symbol	**Description**
H_i	Inertia, (s)
H	Equivalent inertia, (s)
$\Delta\omega_i$	Frequency deviation, [pu]
$\Delta p_{G,i}$	Mechanical power deviation, [pu]
$\Delta p_{D,i}$	Load power deviation, [pu]
$\Delta p_{G,tot}$	Total mechanical power deviation, [pu]
$\Delta p_{D,tot}$	Total load power deviation, [pu]
$a_{1,i}$, $a_{2,i}$	Poles of the generic second-order system
$b_{1,i}$, $b_{1,i}$	Zeros of the generic second-order system
K_i	Inverse of the droop in pu on $M_{base,i}$
$\Delta p_{i,max}$	Maximum output increase of generator *i*, [pu]
$\Delta p_{i,min}$	Minimum output increase of generator *i*, [pu]
$M_{base,i}$	Rating of generator *i*, [MW]
S_{base}	System base, [MW]
$OFRes$	Outage factor for RES

Ps	Total scheduled amount for RES, [MW]
$p_{G,i}$	Scheduled amount for unit *i*, [MW]
Del	Total amount of RES deloaded, [MW]

3.4.2. MODELLING OF THE SYSTEM

The dynamic simulations are formulated with a system frequency dynamic model of second order that simplifies the power system model and at the same time retains the essential components to reflect frequency dynamics in a sufficiently accurate manner. Wind energy faces the drawback of having a negligible or non-existent inertial response. This leads to a negative impact on frequency stability. In fact, the initial RoCoF increases with decreasing inertia. Since renewable energy sources substitute conventional thermal generating units, the total inertia of the system is smaller and as a result, the frequency deviations are larger. Under frequency load shedding (UFLS) schemes protect the system against low frequency situations. There are different designs for UFLS schemes which are implemented depending on the characteristics of the system. By enhancing the frequency response, less UFLS is expected to happen, as explained in 1.2.4. The complete SFD model is explained in [1] and consists of n_g generators which include thermal units and wind turbines, with n_g turbine-governor models. The modelling of each generating unit is shown in Figure 5.

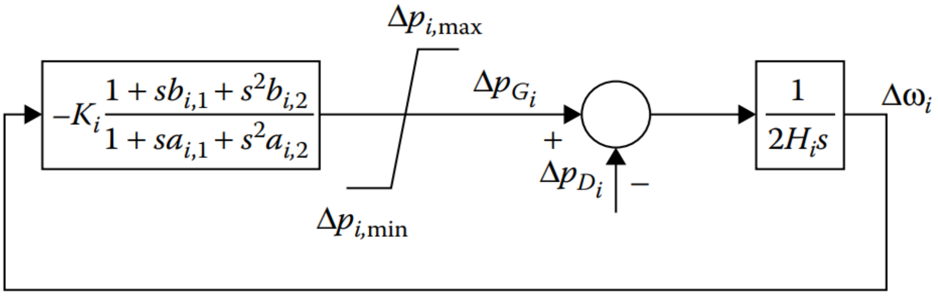

Fig. 5. Model of the *i*th generating unit. Source: [1].

The equation of motion of the *i*th generating unit is defined by:

$$2H_i \mathit{\Delta}\dot{\omega}_i = \Delta p_{G,i} - \Delta p_{D,i} \tag{16}$$

The equation of motion of all the generators in the system is:

$$2\sum_{i=1}^{n_g} H_i * M_{base,i} * \mathit{\Delta}\dot{\omega}_i = \sum_{i=1}^{n_g} M_{base,i} * \Delta p_{G,i} - \sum_{i=1}^{n_g} M_{base,i} * \Delta p_{D,i} \tag{17}$$

The dynamics of the generic second-order system of the *i*th generating unit are described by the following set of nonlinear equations, where x is the state variable that models the relationship between the frequency deviation (Δω) and the power deviation ($\mathit{\Delta} p'_{G,i}$).

$$\begin{bmatrix} \Delta\dot{x}_{1tg,i} \\ \Delta\dot{x}_{2tg,i} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -{}^{1}/_{a_{1,i}} & -{}^{a_{1,i}}/_{a_{2,i}} \end{bmatrix} \begin{bmatrix} \Delta x_{1tg,i} \\ \Delta x_{2tg,i} \end{bmatrix} + K_i \begin{bmatrix} 0 \\ {}^{1}/_{a_{2,i}} \end{bmatrix} \Delta\omega \tag{18}$$

$$\mathit{\Delta} p'_{G,i} = \begin{bmatrix} 1 - \frac{b_{2,i}}{a_{2,i}} & b_{1,i} - \frac{a_{2,i} \cdot b_{2,i}}{a_{2,i}} \end{bmatrix} \begin{bmatrix} \Delta x_{1tg,i} \\ \Delta x_{2tg,i} \end{bmatrix} + K_i \cdot \frac{b_{2,i}}{a_{2,i}} \Delta\omega \tag{19}$$

$$\mathit{\Delta} p_{G,i} = \max\left(\mathit{\Delta} p_{i,min}, \min\left(\mathit{\Delta} p_{i,max}, \mathit{\Delta} p'_{G,i}\right)\right) \tag{20}$$

The system base is the sum of the ratings of every generator:

$$S_{base} = \sum_{i=1}^{n} M_{base,i} \tag{21}$$

To normalize the equations to the size of the isolated power system, equation (17) is divided by *S_{base}:*

$$2 \cdot \sum_{i=1}^{n_g} H_i \frac{M_{base,i}}{S_{base}} \mathit{\Delta}\dot{\omega}_i = \sum_{i=1}^{n_g} \frac{M_{base,i}}{S_{base}} \cdot \Delta p_{G,i} - \sum_{i=1}^{n_g} \frac{M_{base,i}}{S_{base}} \cdot \Delta p_{D,i} \tag{22}$$

The equivalent inertia *H* of the system is:

$$H = \sum_{i=1}^{n_g} \frac{H_i \cdot M_{base,i}}{S_{base}} \tag{23}$$

Combining equations (22) and (23), the uniform frequency deviation is described by the average frequency deviation as the next equation shows:

$$2H\Delta\dot{\omega} = \Delta p_{G,tot} - \Delta p_{D,tot} \tag{24}$$

Given that equation (22) is normalized to *S_{base}*, the gain of the generic turbine-governor system model K_i (which is the inverse of the droop) must also be expressed according to S_{base}:

$$K_i = \frac{K_i.M_{base,i}}{S_{base}} \tag{25}$$

3.4.3. MODELLING OF THE WIND GENERATION

In [3] wind turbines are modelled as thermal units with zero inertia H_i and zero gain K_i unless they emulate inertia or operate below the maximum power point tracking (MPPT). In the cases where deloading is considered, wind units work below the MPPT and are able to participate in the recovery of the frequency response when an outage happens. The control strategy of wind turbines is presented in Fig. 6 and has been applied in different literature studies such as [9], [40], [41] and [37]. This configuration implements the inertia emulation control loop and is capable of affording steady-state power sharing. This same method is used in this worl. Wind system parameters for dynamic simulation are taken from [37] and showed in Annex B.

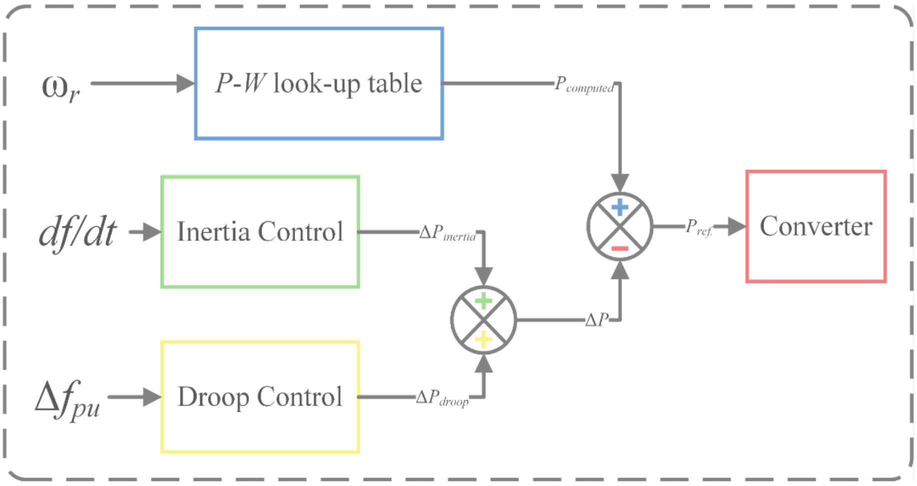

Fig. 6. Control strategy of wind turbines. Source: [10].

For the purpose of this work, an outage of wind power generation of 10% has been considered for all cases ($OFRes = 0.1$), following the generators information provided by [12] for Tenerife and La Palma, where the biggest wind farm covers around that percentage of the total demand of the system. This percentage affects the total power available of the wind unit, including deloading, spilled and scheduled.

Wind generation has been modelled as two conventional units. Both are connected when RES power is scheduled. One of them represents the remaining power and the other one represents the outage that takes place and that is simulated in the frequency dynamics model. Their scheduled power and their maximum positive or negative power deviation are shown in Table II.

	Remaining unit	**Outage unit**
$p_{G,i}$	$Ps * (1 - Del) * (1 - OFRes)$	$Ps * (1 - Del) * OFRes$
$\Delta p_{i,max}$	$Ps * Del * (1 - OFRes)$	$Ps * Del * OFRes$

Table II. RES specifications.

4. CASE STUDIES AND SCENARIOS

4.1. DESCRIPTION OF CASE STUDIES

The Energy Strategy for the Canary Islands in 2025 has as its main objective to drive the electrical power network to lower carbon levels. Among others, key goals for the 2015-2025 period with respect to renewable, include accomplishing a 45% of the total electricity produced by RES by year 2025. This would require multiplying the current available amount of renewable energy by more than five. To increase this amount of available wind power, on-shore as well as off-shore wind units will be installed. Researchers in [42] have assessed the off-shore wind capability of the Canary Islands and inferred that 420 MW of this kind of technology can be introduced in La Palma, which corresponds to more than 40 times the current amount installed.

To achieve realistic results, the inputs used in this work are the most recent actual demand and RES generation of Tenerife and La Palma, which have been obtained by Spanish islands operators. For the future cases and scenarios, the demand is scaled up by forecasted multipliers for the corresponding year. The remaining required inputs, which include available power plants and their technical data sheet with their cost functions, up and down time limitations, capacities and ramping limitations have also been obtained by the Spanish operators.

4.1.1. LA PALMA

The total demand in La Palma in year 2018 was almost 280 GWh, with an average hourly demand of 31.7 MWh, mainly supplied by eleven Diesel generating units. According to [17], the installed capacity of the power system of La Palma reaches almost 118 MW, where about 6% (7MW) of the installed capacity corresponds to wind power generation. In total, renewable generation covers around 10% of the total demand.

The technical data regarding the thermal generators is shown in Table III: gain (K) on Mbase, inertia (H) on Mbase, maximum power, minimum power, and the state space representation matrices (B1, B2, A1 and A2).

BUS	K (on MBASE =1/R)	H (s) (on MBASE)	MBASE (MVA)	Pmax (MW)	Pmin (MW)	B1	B2	A1	A2
LGCHD06	20	1.75	5.4	4	2.4	1.82	0	17.31	0.79
LGCHD07	20	1.75	5.4	4	2.4	1.82	0	17.31	0.79
LGCHD08	20	1.75	5.4	4	2.4	1.82	0	17.31	0.79
LGCHD09	20	1.73	6.3	4.3	2.8	1.8	0	17.11	0.85
LGCHD010	20	2.16	9.4	6.7	3.3	3.16	0	25.03	9.8
LGCHD011	20	1.88	9.6	6.7	3.3	2.05	0	18.88	1.68
LGCHD012	20	2.1	15.75	11.5	6.6	3.21	0	25.32	9.7
LGCHD013	20	2.1	14.5	11.2	6.6	3.21	0	25.32	9.7
LGCHD014	20	2.1	14.5	11.5	6.6	3.21	0	25.32	9.7
LGCHD015	20	2.1	14.5	11.5	6.6	3.21	0	25.32	9.7
LGCHGM2	21.25	6.5	26.82	21	4.9	0.83	0	5.2	3.4

Table III. Technical information of the conventional generators in La Palma.

4.1.2. TENERIFE

Total demand in Tenerife in year 2018 mounts up to almost 3,690 GWh, with an average hourly demand of 420.8 MWh. Of the total annual demand, two combined cycle units (gas and steam) generate around 45.5%, 4 steam units cover around 35.5%, 5 diesel units deliver 7%, 5 thermal gas units generate 3.5% and the rest is provided by RES. The most expensive thermal units are expected to be replaced by renewable units before 2025. Figure 7 shows the amount of power delivered from one unit of wind or solar in each season of the year from all RES sites in Tenerife island. Solid lines denote wind generation and dashes lines denote solar generation.

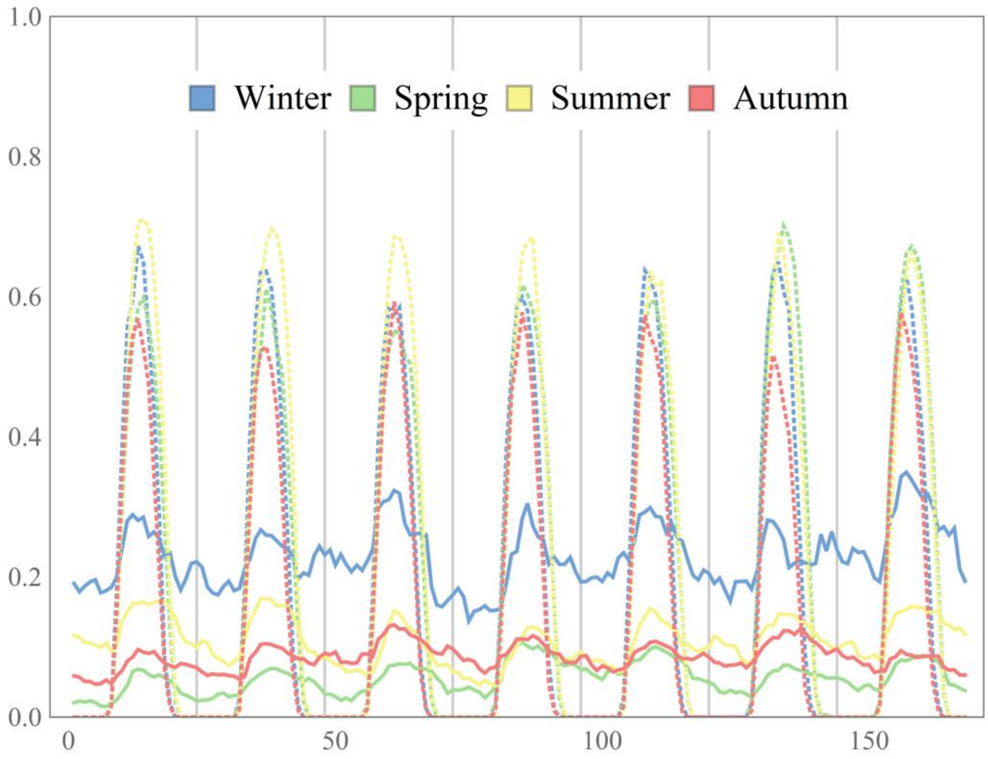

Fig. 7. Cumulative generation of wind and solar in Tenerife island per unit during a week in each season. Source: [10].

The technical data of Tenerife's thermal generators is shown in Table IV.

BUS	**K (on MBASE =1/R)**	**H (s) (on MBASE)**	**MBASE (MVA)**	**Pmax (MW)**	**Pmin (MW)**	**B1**	**B2**	**A1**	**A2**
GISOG01A	39.91	5	32	21.6	4.85	2.51	0	4.02	1.95
GISOG01B	39.91	5	32	21.6	4.85	2.51	0	4.02	1.95
ARONGA1	35.95	5	38.13	24.3	4.85	2.38	9	3.93	1.85
ARONGA2	35.95	5	38.13	24.3	4.85	2.38	9	3.93	1.85
GRLLD01	0	0	0	0	0	0	0	0	0
GRLLD02	25	1.5	30	19.1	14.8	0	0	0.35	0.01
GRLLV01	16.67	5.6	100	74.2	29.3	0	0	10	1.75
GRLLV02	16.67	5.6	100	74.2	29.3	0	0	5.35	1.75
GRLLG02	0	0	0	0	0	0	0	0	0
GRLCCC1_G3	32	5	50	39.2	6.8	2.25	0	3.85	1.75
GRLCCC1_G4	20.21	5.08	92.78	68.7	9.7	0	0	0.43	0.09
GRLCCC1_V	16.67	5.08	92.78	48.6	3.23	0	0	5.35	1.75
GRLCCC2_G5	20.21	5.08	92.78	75	9.7	0	0	0.43	0.09
GRLCCC2_G6	20.21	5.08	92.78	75	9.7	0	0	0.43	0.09
GRLCCC2_V	16.67	5.08	92.78	56.5	3.23	0	0	5.35	1.75
CNDED01	0	0	0	0	0	0	0	0	0
CNDED02	0	0	0	0	0	0	0	0	0
CNDED03	0	0	0	0	0	0	0	0	0
CNDEG01	0	0	0	0	0	0	0	0	0
CNDEG02	0	0	0	0	0	0	0	0	0
CNDEG03	0	0	0	0	0	0	0	0	0
CNDEV05	0	0	0	0	0	0	0	0	0
CNDEV06	0	0	0	0	0	0	0	0	0

Table IV. Technical information of the conventional generators in Tenerife.

4.2. DEFINITION OF SCENARIOS

Different scenarios with an increasing wind installed capacity, in sample weeks of each season (winter, spring, summer and autumn) have been considered in order to analyse the technical impacts when they are able to provide frequency regulation. Since this work follows the line of research of reference [10], the cases and scenarios considered will be the same (the case of RES provided down spinning effect is excluded, since the model will simulate generator outages which only require up spinning reserves). Scenario I contemplates the current amount of installed wind capacity. For scenarios II to IV, the current amount is multiplied by 2, 5 and 10, respectively. All the seasons and scenarios are considered for an electricity demand corresponding to the years 2020, 2025 and 2030. The aim is to acknowledge both the economic and technical impacts of each scenario in the near future.

For each scenario, three cases with different capabilities of providing spinning reserve by RES are defined.

- Case A: This case is the current practice of Spanish operators in island power systems. Wind and solar sources cannot provide frequency regulation (the deloading factor is set to zero). The total amount of reserve required must be fully provided by thermal units. This is the base case.
- Case B: WTGs are able to provide up spinning reserve. A constant deloading factor of 10% of the total available power is applied for the entire time frame. So, in each hour, 10% of the total available wind generation is deloaded and specified as up spinning reserve. Emulation of inertia is also included.
- Case C: The possible amount of deloading is defined as a coefficient that can vary between 0 and 15% of the total available wind generation and whose optimal amount will be decided by the unit commitment optimization problem in each hour. Emulation of inertia is also included.

Figure 9 shows all the considered states. The weekly unit commitment model is performed for 3 different cases (A, B and C), 4 sample weeks that represent the different seasons of a year (winter, spring, summer and automn) and 4 wind penetration scenarios (I, II, III and IV) for each; composing 48 weekly unit commitments for each year of study. This approach is employed for three different years: 2020, 2025 and 2030. In total, 144 simulations have been completed for each island.

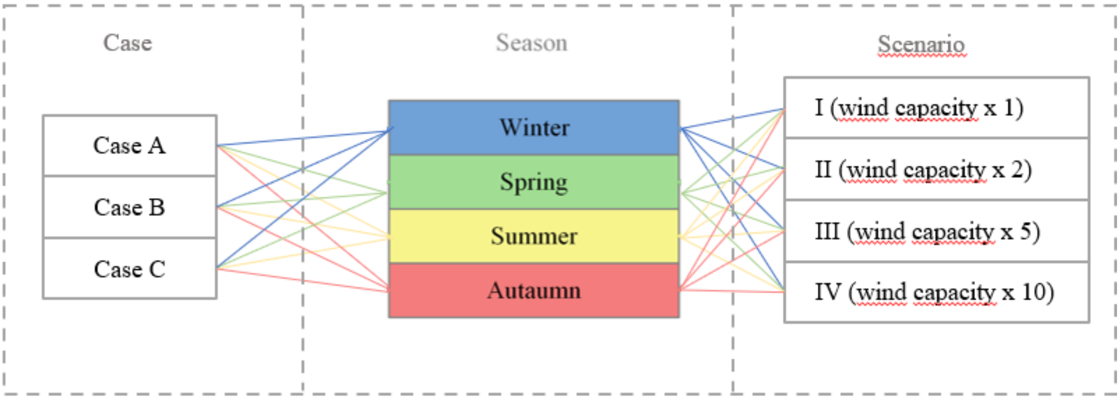

Fig. 8. Considered states.

5. RESULTS

In order to analyse the results from a technical point of view, different input states are compared, regarding the following key performance indicators which have been defined according to the frequency ranges stated in subsection 1.2.3:

- The number of severe cases per state: it counts the number of times in all the simulations run in a particular state that the frequency reaches a value lower than 47,5 Hz for more than 3 seconds.
- The number of minimum frequency violations: it counts the number of times in all the simulations run in a particular state that the frequency reaches a value lower than 47 Hz.
- The number of online units in whole week: it counts every unit that is online during the simulations of the considered state.
- The frequency violation percentage: calculated as the percentage of simulations in which the minimum frequency is violated.

When UFLS schemes are activated, the number of sever cases, of minimum frequency violations and the frequency violation percentage are not key performance indicators, since these schemes avoid a bad overall frequency response. To analyse these results and make them comparable with the results of reference [10], the summation of UFLS for all contingencies in all of the hours and the total load shedding cost (LSC) will be analysed in each state. The latest can be obtained by adding the load shedding cost in each hour (C_h), which is computed by multiplying the load shedding of every online generator in every hour (LS) by the Forced Outage Rate of each generator (FOR) and the outage cost (OC) [43].

$$C_h = \sum_h LS \cdot FOR \cdot OC \tag{25}$$

$$LSC = \sum_h C_h \tag{26}$$

The FOR of each type of generator is set arbitrarily, as listed in Table II. The outage cost has been set to be 3000€/MWh to quantify the LSC.

Type of generator	Forced Outage Rate (%)
Diesel	0.004%
Steam	0.002%
Gas	0.0045%
Wind	0.007%

Table V. Forced Outage Rate (FOR) for the generators in La Palma and Tenerife, according to the type.

5.1. LA PALMA

5.1.1. ANALYSIS OF SIMULATIONS WITHOUT UFLS SCHEMES

The seasonal average results of the different states of study for La Palma obtained from the unit commitment model are shown in Figure 9, including the total operation cost, the scheduled amount of thermal and renewable generation and the spilled and deloading amount of renewable. Each case is specified above each bar. The number of the scenario is stated at bottom corner. For each year of study, the results are separated with dashed lines. Above zero is the energy in megawatts and below zero is the total cost in kilo Euros.

Case A is the base case, then incremental or decremental percentage of the results is inscribed in the graphic, comparing to the base case. These results were obtained in [10] and have been adapted to the cases and scenarios contemplated in this work.

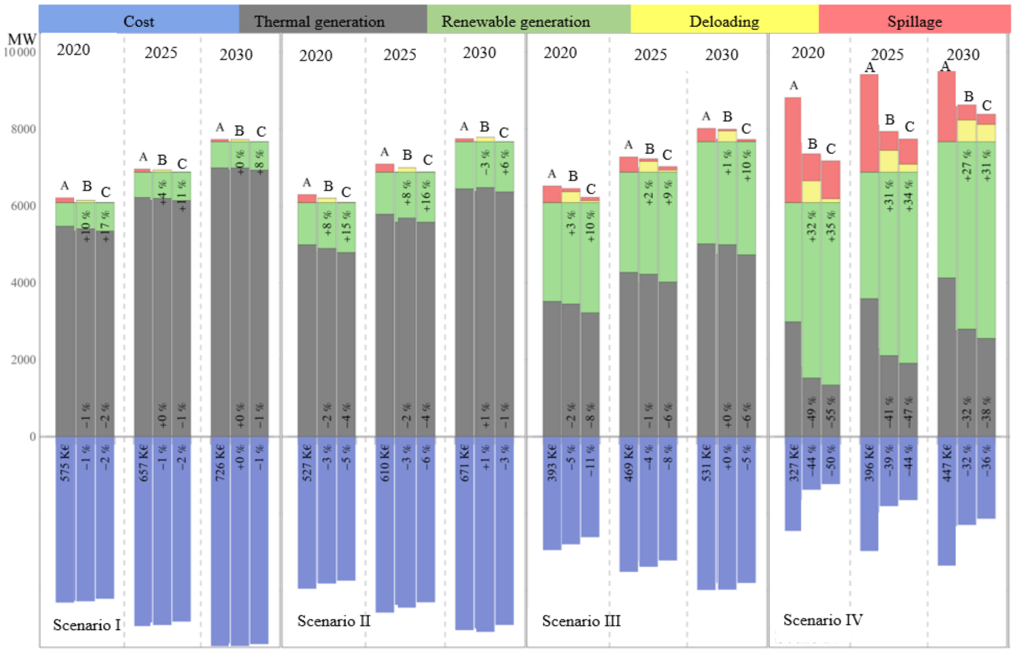

Fig. 9. Average results of 4 seasons obtained for La Palma island in the economic dispatch.

This figure shows that the total cost of generation is generally less when deloading is considered. Further, the amount of power spilled is considerably higher in the base case, in comparison to cases B and C. The main reason is because case A has only thermal sources to cover the up and down reserve requirements, which makes some of them be permanently connected to the net, making it hard for renewables to be connected. Therefore, without enabling RES to provide reserve, increasing the renewable capacity is not recommended, due to the high rating of spillage.

Case B considers a fixed deloading amount of 10% of the total available power. As a result, there is less spillage, and the total operation cost decreases. However, since the deloading amount is not chosen optimally, this case is not recommendable in the hours when the up reserve from the online thermal units is enough. In these cases, it is more cost efficient to deliver power to the power net and cut the deloading.

Figure 10 shows how the reserve is provided in each hour of the week for the different cases of study. The days of the week are separated by vertical lines. The dashed lines represent the up and down reserve requirements in each hour. Since la Palma has a small size, each online unit covers a considerable amount of the total demand. In case A, thermal units must cover both the up and down reserves. As a result, in the hours that require it, some units are online just to ensure that the reserve requirement is met. Then, when the demand is low, only the smaller units are connected, and the bigger ones are shut down. The start-up and shut-down processes translate into higher operation costs. In some of the hours of case B deloading is unnecessary, as the reserve can be fully provided by thermal units and it eliminates some of the available wind generation. In case C, thermal generation can be minimized, since the deloading only occurs in the hours when there is not enough thermal generation up reserve scheduled.

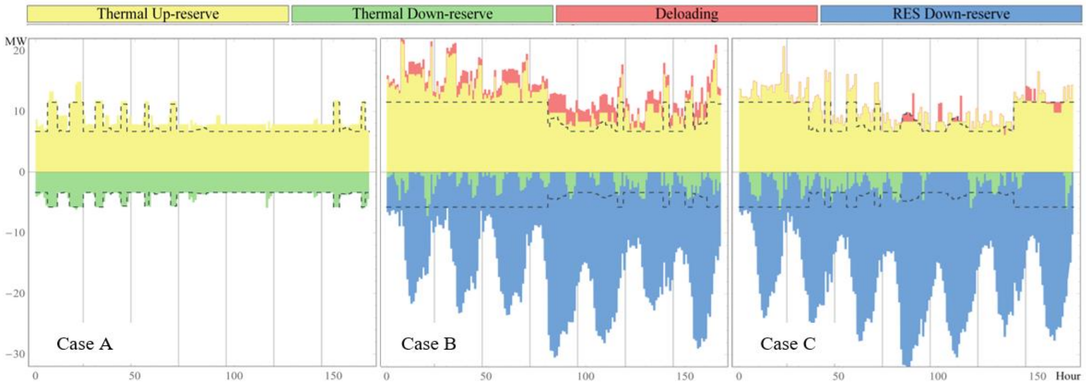

Fig. 10. Reserve provision by different sources in the system for spring sample week 2020, scenario IV.

The seasonal average key performance indicators and the total operation cost for different scenarios and cases for La Palma island are shown in Table VI. The operation cost has been obtained from the economic dispatch, as in reference [10]. Incremental or decremental percentages are obtained comparing to the base case. Since the key performance indicators for the technical response (except for the number of online units) are correlated, only the number of severe cases is represented in Figure 11 for a better analysis of the results, where the daily operation cost and the expected cost for UFLS in one year are also shown. Above zero is the cost in Kilo Euros and below zero is the number of severe cases. Red bars represent the average seasonal weekly UC dispatch cost [10]. Green bars represent the expected cost of UFLS for the simulations run under current UFLS schemes, while yellow bars represent the number of severe cases for the simulations run without UFLS schemes.

			Number of online units in whole week	Number of severe cases	Number of minimum frequency violations	Frequency violation percentage	Cost
Scenario I	2020	A	1329	202	199	15	575K€
		B	1358(+2%)	175(-13%)	169(-15%)	12.4(-17%)	-1%
		C	1289(-3%)	179(-11%)	175(-12%)	13.6(-9%)	-2%
	2025	A	1467	166	144	9.8	657K€
		B	1477(+1%)	151(-9%)	127(-12%)	8.6(-12%)	-1%
		C	1420(-3%)	286(+72%)	224(+56%)	15.8(+61%)	-2%
	2030	A	1452	295	215	14.8	726K€
		B	1533(+6%)	255(-14%)	192(-11%)	12.5(-15%)	+0%
		C	1544(+6%)	202(-32%)	141(-34%)	9.1(-38%)	-1%
Scenario II	2020	A	1294	229	217	16.8	527K€
		B	1165(-10%)	271(+18%)	257(+19%)	22.1(+32%)	-3%
		C	1206(-7%)	280(+22%)	283(+30%)	23.5(+40%)	-5%
	2025	A	1438	188	178	12.4	610K€
		B	1373(-5%)	182(-3%)	159(-11%)	11.6(-6%)	-3%
		C	1487(+3%)	109(-42%)	113(-37%)	7.6(-39%)	-6%
	2030	A	1452	243	187	12.9	671K€
		B	1460(+1%)	176(-28%)	140(-25%)	9.6(-26%)	+1%
		C	1516(+4%)	165(-32%)	122(-35%)	8(-38%)	-3%
Scenario III	2020	A	1308	22	11	0.8	393K€
		B	1077(-18%)	111(+405%)	132(+1100%)	12.3(+1357%)	-5%
		C	1051(-20%)	192(+773%)	209(+1800%)	19.9(+2265%)	-11%
	2025	A	1374	85	81	5.9	469K€
		B	1288(-6%)	73(-14%)	83(+2%)	6.4(+9%)	-4%
		C	1215(-12%)	107(+26%)	128(+58%)	10.5(+79%)	-8%
	2030	A	1266	266	247	19.5	531K€
		B	1308(+3%)	117(-56%)	108(-56%)	8,3(-58%)	-44%
		C	1302(+3%)	154(-42%)	145(-41%)	11.1(-43%)	-50%
Scenario IV	2020	A	1241	4	4	0.3	327K€
		B	807(-35%)	12(+200%)	13(+225%)	1.6(+389%)	-44%
		C	781(-37%)	37(+825%)	45(+1025%)	5.8(+1660%)	-50%
	2025	A	1232	96	90	7.3	396K€
		B	913(-26%)	50(-48%)	57(-37%)	6.2(-15%)	-39%
		C	818(-34%)	86(-10%)	97(+8%)	12.2(+67%)	-44%
	2030	A	1206	212	205	17	447K€
		B	937(-22%)	91(-57%)	99(-52%)	10.6(-38%)	-32%
		C	965(-20%)	94(-56%)	109(-47%)	11.3(-34%)	-36%

Table VI. Results of La Palma under no UFLS scheme.

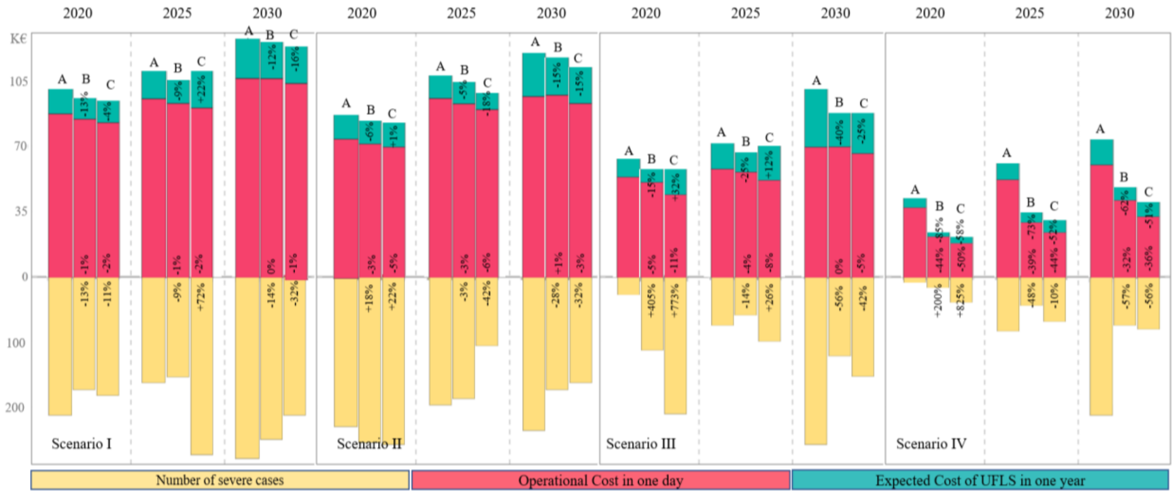

Fig. 11. The average technical and economic results of 4 seasons for La Palma island.

UFLS schemes have not been activated. Therefore, there is a high number of severe cases and frequency violations. To analyse these results, it is important to compare the metrics between the cases and not the unrealistic values themselves, although in island power systems every outage has an important impact on the frequency response.

Results show that for the current demand (year 2020), the frequency response only improves for the cases with deloading capability (cases B and C) if the wind penetration is low (Scenario I). For instance, in 2020 the number of severe cases for case B diminishes 13% for Scenario I, and increases +18%, +405% and +200% with respect to base case A for senarios II, III and IV respectively. As with a low demand in a small island like La Palma the number of online units is very low, the outage of one of them has an important impact on the frequency response of the system. If the wind generation increases, less conventional units are connected and when the wind unit is lost, the impact in the frequency response is considerably high. It is important to highlight that comparing different cases implies comparing different economic dispatches, as the online units for the same demand and wind penetration vary from one case to another.

When the demand increases, which will happen in the future years, more online units are connected, and, since the demand covered by each of them is less, their outage does not have such a high impact on the frequency response. It can be seen that a fixed deloaded capability (case B) always improves base case A, for every wind penetration scenario (Scenarios I, II, III and IV). In this increased demand scenarios of 2025 and 2030, for high wind penetration scenario (III and IV), case C worsens the dynamic response with respect to case B.

For the case of having the current demand and more RES installed the frequency response does not improve, but for future years, to consider a fixed deloading factor (case B) positively affects the frequency response. It is also worth mentioning that in year 2020, the number of severe cases is always better for case B (fixed deloading factor) compared to case C (variable deloading factor). This proves that the deloading factor that is optimal from an economic point of view (case C) is not necessarily optimal for the frequency response enhancement. In fact, case C does not always improve the frequency response of the system and it has no clear correlation with the demand and the wind penetration (for instance, in 2030 case C improves case B in scenario I and II and worsens in III and IV). This unexpected result can be explained with the variable deloading factor, which only tries to minimize the cost in each hour. Since the UC schedules a minimum spinning reserve requirement neglecting frequency dynamics, wind generation is only deloaded in the hours that not enough thermal generation up reserve is scheduled, which means that less deloading is scheduled compared with case B, to serve as power reserve. When a contingency occurs, it has less power to serve as reserve and can result in a worse frequency response.

When deloading is considered, the economic dispatch changes, and the number of online units decreases because some thermal units that in case A are only connected to cover the reserve requirements can now be disconnected.

Figure 12 shows the frequency response of the system in the first hour of one sample week with the current demand and a high wind penetration scenario (scenario IV). Each response represents the frequency response of the system to the outage of one of the online units. The outage of every thermal unit, as well as the outage of a 10% of RES is shown. This image illustrates how the frequency response does not change much from the base case to the cases with deloading when the demand of the system is the current demand (year 2020). The steady state is achieved almost at the same time and its final frequency deviation is very similar. The biggest difference is in the initial RoCoF. In the cases with deloading (red and green lines) it is less pending, and the minimum frequency point is achieved slightly sooner. Also, cases B and C are less oscillatory. This figure also shows the limits for severe cases and minimum frequency. UFLS schemes are essential in this case to avoid the violation of the frequency ranges required by the Spanish regulation (Table I).

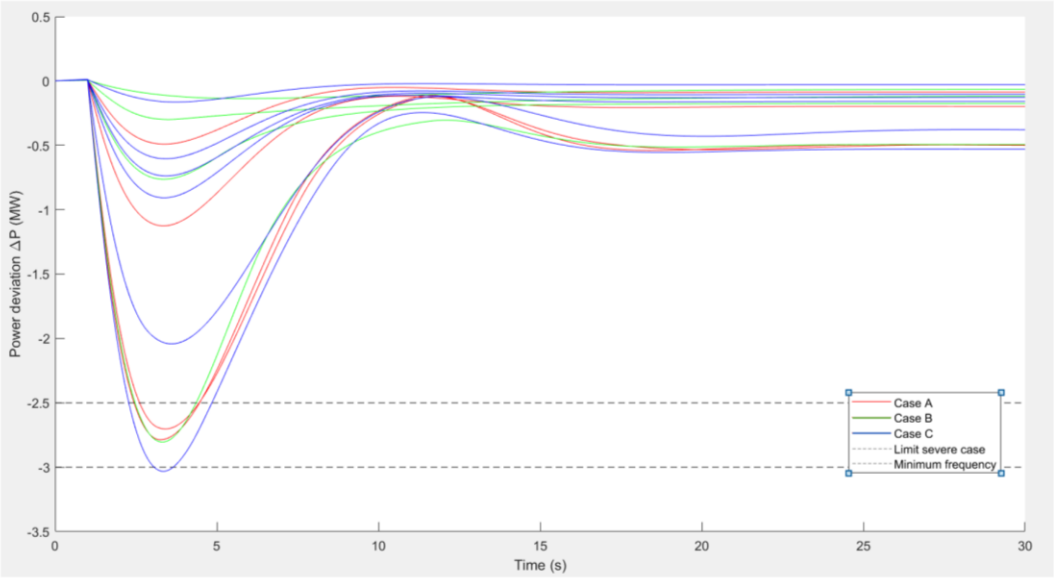

Fig. 12. Frequency response in the first hour of summer in La Palma 2020, scenario IV for case A, B and C under no UFLS scheme.

5.1.2. ANALYSIS OF SIMULATIONS UNDER CURRENT UFLS SCHEMES

The results of the simulations run in La Palma under current UFLS scheme are shown in Table VII. In Figure 11, the expected cost of UFLS in one year is shown. This value is very low in comparison to the operational cost, due to the low forced outage rate of the generators.

RESULTS FOR LA PALMA UNDER CURRENT UFLS					
		I	**II**	**III**	**IV**
2020	**A**	2830	2889	1728	2039
	B	2451 (-13%)	2727 (-6%)	1475 (-15%)	309 (-85%)
	C	2713 (-4%)	2909 (1%)	2279 (32%)	819 (-60%)
2025	**A**	2958	2894	2182	2624
	B	2705 (-9%)	2757 (-5%)	1646 (-25%)	716 (-73%)
	C	3613 (22%)	2369 (-18%)	2450 (12%)	1230 (-53%)
2030	**A**	4346	3745	3527	3401
	B	3828 (-12%)	3176 (-15%)	2107 (-40%)	1304 (-62%)
	C	3639 (-16%)	3176 (-15%)	2644 (-25%)	1617 (-52%)

Table VII. The summation of all UFLS in La Palma.

When we move forward to the realistic case where UFLS schemes are in place, we can check whether a better dynamic performance translates in less load shedding and in this way less UFLS system cost.

Results show that for the same demand in the cases with deloading, the summation of all UFLS for all contingencies is reduced when the wind penetration increases. The reason is because wind providing frequency regulation improve the overall frequency response and therefore less load has to be shed. When the demand increases for the same case, more units are connected and each of them covers a high percentage of the total demand. Each contingency has a considerable impact on the frequency response and as a result more load is shed. For higher demands, more load is shed due to the poor the frequency response. This can also be seen in Table VI: for the same scenario if the demand increases, all KPIs of the frequency response worsen because more contingencies are considered. RES providing frequency regulation and spinning reserve always reduces the amount of load to be shed and as a result, its cost. The benefits are more pronounced for higher wind penetration scenarios.

Also, when the deloaded power is fixed in each hour (case B), the results always improve compared to the base case. However, this is not what happens with case C, which considers a variable deloading factor. Results for years 2020 and 2025 only improve only if there is a high wind penetration scenario (IV). For a high demand (2030), they always improve. In fact, when case B and C are compared, B has a better frequency response in almost every scenario.

Figure 13 shows the same frequency response of the system as in Figure 12 but under current UFLS schemes. UFLS schemes prevent severe cases and frequency violations, by shedding a percentage of load. The UFLS change the RoCoF when a certain threshold is reached. In case A because of the high initial RoCoF, the amount of load shed is higher than the amount of power lost in the outage. As a result, the power total power provided by the online units is higher than the total demand of the system, which translates into a frequency overshoot.

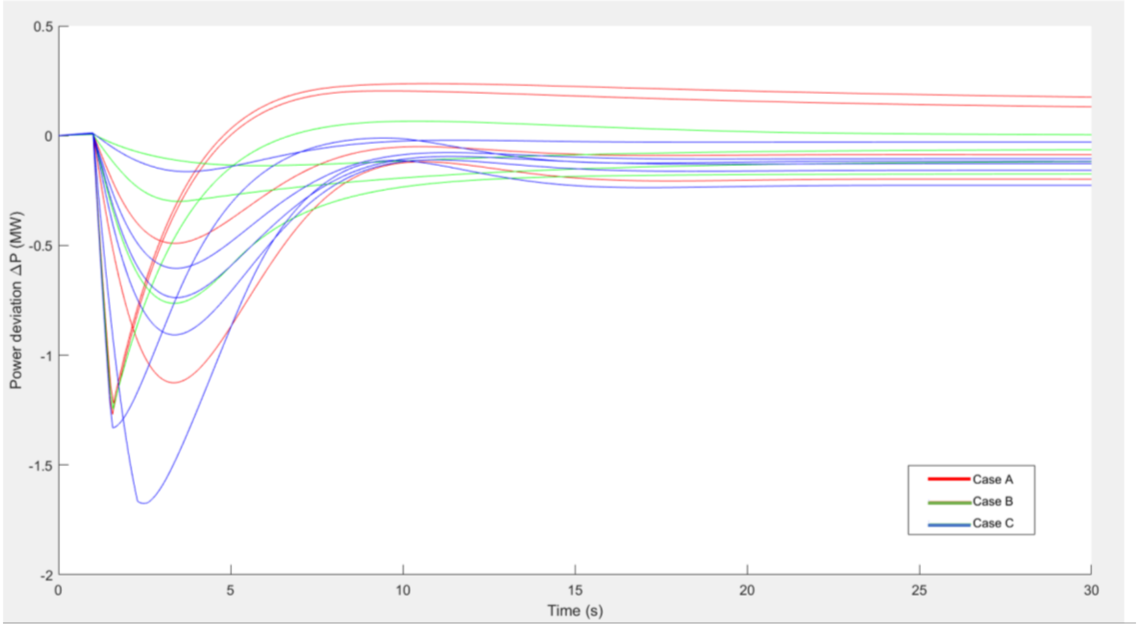

Fig. 13. Frequency response in the first hour of summer in La Palma 2020, scenario IV for case A, B and C under current UFLS scheme.

5.2. TENERIFE

5.2.1. ANALYSIS OF SIMULATIONS WITHOUT UFLS SCHEMES

For a bigger island like Tenerife, the main qualitative conclusions obtained for La Palma can be verified. The average results of all the seasons are presented in detail in Figure 14.

Again, results show that considering a constant deloading percentage is not economically advisable for the cases when the RES penetration is low, especially when the demand increases, since the share of thermal generation also increases. In case C, no deloading is scheduled when the available power generation is low, and the costs are considerably reduced.

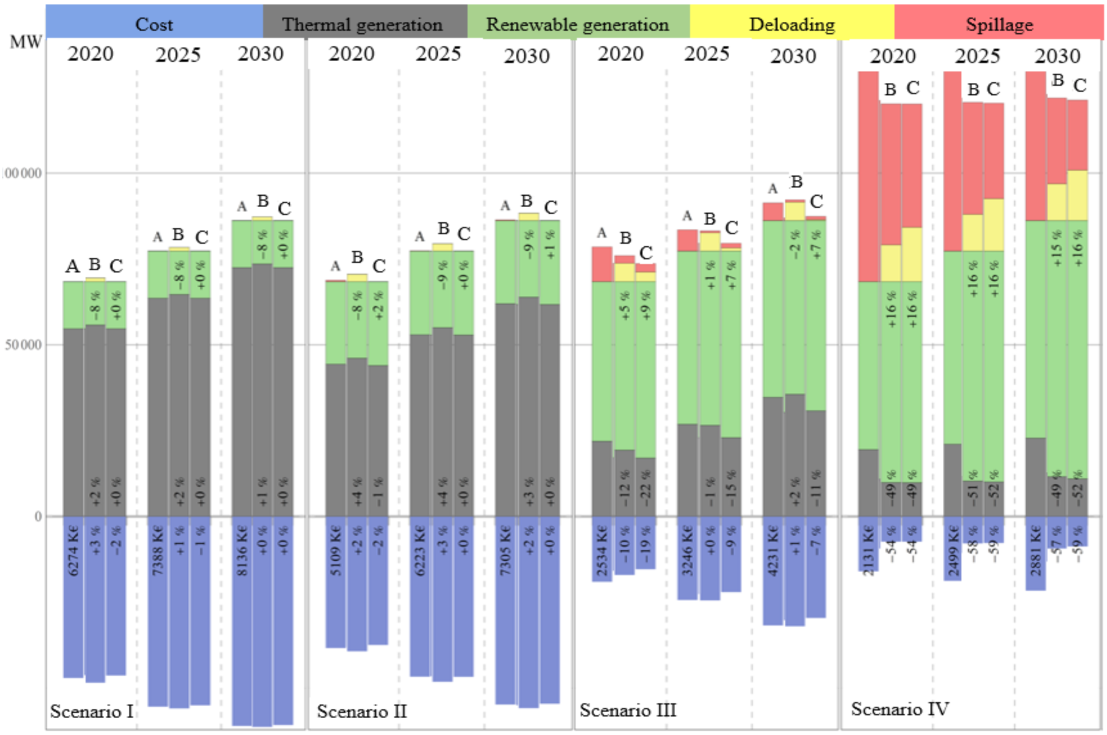

Fig. 14. Average results of 4 seasons obtained for Tenerife island in the economic dispatch.

Figure 15 shows how the thermal and renewable sources participate in order to cover reserve constraints. In cases B and C, deloading is important for the cases when the RES penetration is high. Since the amount of scheduled RES is the boundary of the reserve criteria as stated in equation (8), whenever the amount of RES injected is higher, so is the reserve requirements.

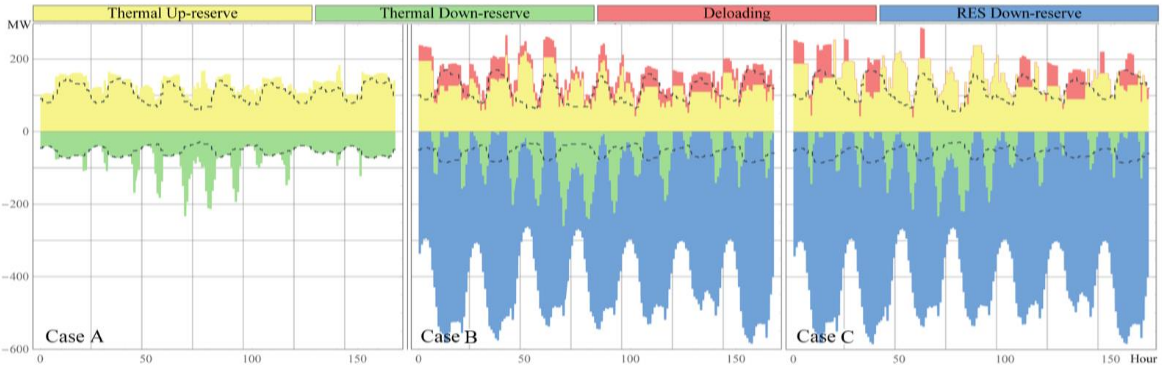

Fig. 15. Reserve provision by different sources in the system for spring sample week 2030, scenario III.

The average KPIs of the technical response are presented in detail in Table VIII. Figure 16 shows the total number of severe cases that occur due to the contingency of each online generating unit, the total operation cost and expected cost of UFLS.

			Number of online units in whole week	Number of severe cases	Number of minimum frequency violations	Frequency violation percentage	Cost
Scenario I	2020	A	1604	159	147	9.2	6274 K€
		B	1629 (+2%)	154 (-3%)	144 (-2%)	8.8 (-4%)	+3%
		C	1625 (+1%)	149 (-6%)	145 (-1%)	8.9 (-3%)	-2%
	2025	A	1706	244	236	13.8	7388 K€
		B	1738 (+2%)	232 (-5%)	215 (-9%)	12.4 (-11%)	+1%
		C	1729 (+1%)	244 (+0%)	230 (-3%)	13.3 (-4%)	-1%
	2030	A	2005	255	234	11.7	8136 K€
		B	2069 (+3%)	238 (-7%)	225 (-4%)	10.9 (-7%)	+0%
		C	2072 (+3%)	246 (-4%)	220 (-6%)	10.6 (-9%)	+0%
Scenario II	2020	A	1403	167	166	11.8	5109 K€
		B	1402 (+0%)	165 (-2%)	163 (-2%)	11.6 (-2%)	+2%
		C	1401 (+0%)	163 (-2%)	163 (-2%)	11.6 (-2%)	-2%
	2025	A	1644	122	107	6.5	6233 K€
		B	1602 (-3%)	140 (+15%)	129 (+21%)	6.3 (+24%)	+3%
		C	1562 (-5%)	112 (-8%)	98 (-8%)	8.1 (-4%)	+0%
	2030	A	1788	165	146	8.2	7305 K€
		B	1723 (-4%)	181 (+10%)	159 (+9%)	9.2 (+9%)	+2%
		C	1773 (-1%)	174 (+5%)	154 (+5%)	8.7 (+5%)	+0%
Scenario III	2020	A	1179	49	15	1.3	2534 K€
		B	834 (-29%)	5 (-90%)	5 (-67%)	0.6 (-53%)	-10%
		C	809 (-31%)	23 (-53%)	24 (+60%)	3 (+133%)	-19%
	2025	A	1309	27	25	1.9	3246 K€
		B	1108 (-15%)	9 (-67%)	9 (-64%)	0.8 (-57%)	+0%
		C	1094 (-16%)	7 (-74%)	7 (-72%)	0.6 (-66%)	-9%
	2030	A	1416	21	21	1.5	4231 K€
		B	1297 (-8%)	17 (-10%)	17 (-19%)	1.3 (-12%)	+1%
		C	1283 (-9%)	11 (-48%)	11 (-48%)	0.9 (-42%)	-7%
Scenario IV	2020	A	1150	51	17	1.5	2131 K€
		B	674 (-41%)	1 (-100%)	0 (-100%)	0 (-100%)	-54%
		C	672 (-42%)	0 (-98%)	1 (-94%)	0.1 (-90%)	-54%
	2025	A	1282	14	9	0.7	2499 K€
		B	681 (-47%)	0 (-100%)	0 (-100%)	0 (-100%)	-58%
		C	684 (-47%)	0 (-100%)	0 (-100%)	0 (-100%)	-59%
	2030	A	1266	0	0	0	2881 K€
		B	716 (-43%)	0	0	0	-57%
		C	701 (-34%)	0	0	0	-59%

Table VIII. Results for Tenerife under no UFLS scheme.

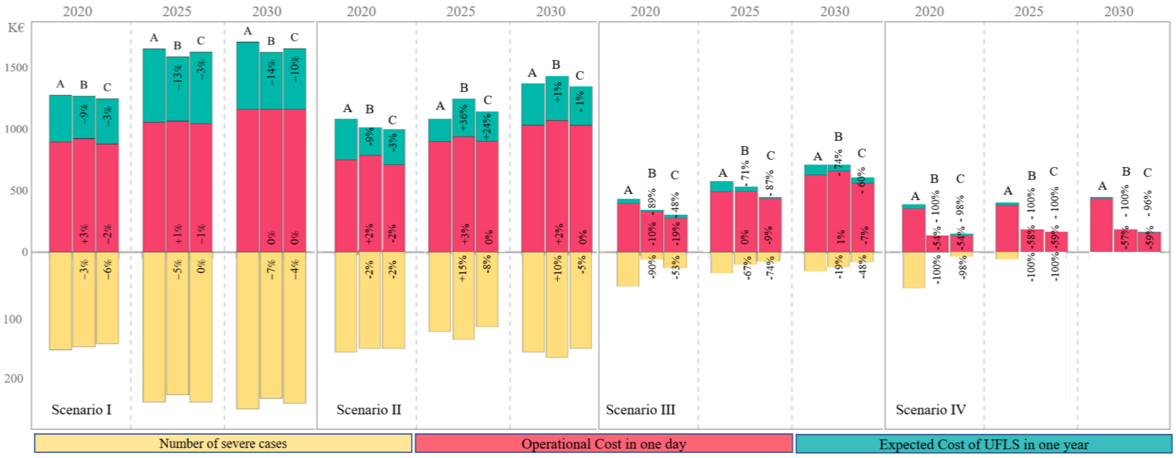

Fig. 16**.** The average technical and economic results of 4 seasons for Tenerife island.

Results show that deloading always improves the frequency response, but again, the optimal deloading factor from an economical point of view is not necessarily the value that gives the best frequency response.

Case B considers a constant deloading factor of 10%. It is deduced from its results that in some of the considered states, deloading is unnecessary, as the frequency response is worse than in case A. The reason is because two different dispatches are being compared. Having a constant deloading factor is not economically advisable either when the wind penetration is low. However, in those particular states, having a variable deloading factor (case C) does improve the response and optimize the total cost. When case C is compared to case A, the number of severe cases and of minimum frequency violations are reduced, but not always when it is compared to case B. Results also show that for future wind scenarios the frequency response of the system improves in comparison to the current installed wind energy. In addition, if wind provides frequency regulation, then the frequency response of the system is extremely good, and there are no severe cases. This means that load shedding is not needed, and the power network is more secure and stable.

Mostly the total cost (operational and expected) is higher for the case without deloading capability. In terms of cost, case C always improves the results in comparison to case B. This is because most of the total cost comes from the operation of the system. Given that the deloading factor is such that the operational cost is minimized, case C has the best results. This is especially noticeable for high wind penetration scenarios (III and IV), which lead to a great cost reduction, as well as an optimal frequency response. Figure 9 shows that there is a correlation between the technical and the economic responses of the system. A higher number of severe cases translates into a higher total cost of the state.

Figure 17 shows the frequency response of the system in the first hour of one sample week with high demand and a high wind penetration scenario (scenario III). It shows that deloading clearly improves the frequency response. The bad frequency response of case A is due to the contingency of the wind unit. As the wind penetration is high and none of it is deloaded, the wind unit covers most of the demand of the system and its outage deeply affects the overall response. In the cases with deloading, more units are connected to cover the high demand, providing better frequency dynamics in the system. The steady-state frequency deviation and the recovery time are reduced in cases B and C. In addition, the minimum frequency deviation and the initial RoCoF also improve when there is deloading, and the response is less oscillatory. Because of its big size, Tenerife has more units connected than smaller islands, and the contingency of each of them has a smaller impact in the overall frequency response. The number of severe cases, minimum frequency violation and the frequency violation percentage are smaller than in La Palma and in Figure 10 and none of the frequency limits is reached. Even if the amount of wind lost is very high, as happens in Figure 16, the rest of online units will manage to regulate the dynamics better than in a smaller system. It can be concluded that the size of the island power system is essential for the frequency response. More online units participating in the recovery of the system translates into a lower impact in the frequency dynamics.

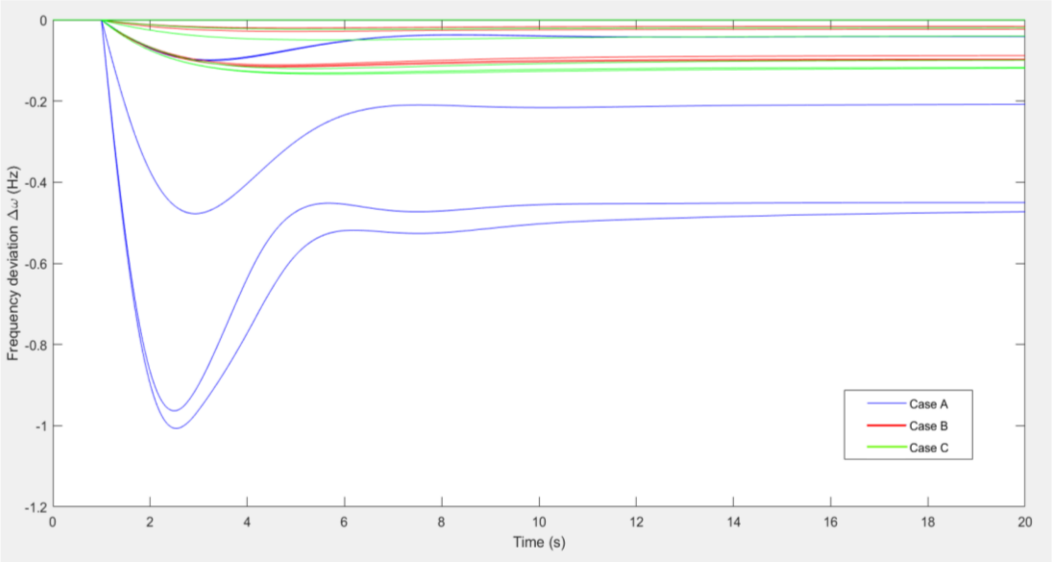

Fig. 17. Frequency response in the first hour of summer in Tenerife 2030, scenario III for case A, B and C.

5.2.1. ANALYSIS OF SIMULATIONS UNDER CURRENT UFLS SCHEMES

The results of the simulations run in Tenerife under current UFLS schemes are shown in Table VII. The expected cost of UFLS in one year is shown in Figure 17.

TABLE X. RESULTS FOR TENERIFE UNDER CURRENT UFLS

		I	II	III	IV
2020	**A**	21293	24794	5142	5328
	B	19339 (-9%)	22057 (-11%)	552 (-89%)	0 (-100%)
	C	20682 (-3%)	24229 (-2%)	3137 (-39%)	148 (-97%)
2025	**A**	21293	24794	5142	5328
	B	19339 (-9%)	22057 (-11%)	552 (-89%)	0 (-100%)
	C	20682 (-3%)	24229 (-2%)	3137 (-39%)	148 (-97%)
2030	**A**	21293	24794	5142	5328
	B	19339 (-9%)	22057 (-11%)	552 (-89%)	0 (-100%)
	C	20682 (-3%)	24229 (-2%)	3137 (-39%)	148 (-97%)

Table IX. The summation of all UFLS for Tenerife under current UFLS scheme.

For the same demand, if the wind penetration increases, the summation of UFLS for all contingencies remains constant in all of the cases. This happens even in case A, where an increasement of this KPI would have been expected. The reason is because even if RES does not provide frequency regulation, less online units are connected, there are fewer contingencies, and less load has to be shed. Also, as the wind increases, the amount of load shedding is reduced due to an enhancement in the frequency response. As a result, cases B and C shed less load than the base case. In general, the worst the frequency response is, the more amount of load has to be shed to avoid violating the frequency limits imposed by the Spanish regulation. By improving the frequency response, the expected cost of UFLS decreases.

6. CONCLUSIONS AND FUTURE WORK

This work has evaluated the impacts of providing frequency regulation by wind turbines on the overall frequency response of the electrical system. It continues the line of research started in [10], analysing the impacts that this mechanism also has on the overall costs of the operation. Simulations are conducted for La Palma island (small size) and Tenerife (medium size) island with different samples of current and future demand and wind generation scenarios. The aim has been to analyse what technical impacts are expected from enabling renewable energy sources to provide reserve and frequency regulation and to contemplate the relation with the corresponding economic results. The economic operation has been simulated by means of an hourly unit commitment model on a weekly basis. The dynamic simulations have been formulated with a system frequency dynamic model of second order that considers the outage of every online thermal generator and a percentage of wind energy in each hour.

Results show that using wind turbines as reserve and frequency regulation providers is always beneficial from a technical point of view in a big island like Tenerife. For high wind penetration scenarios, the frequency response improves, the system becomes more secure, and in some hours, load does not need to be shed. As a result, the total cost of load shedding is reduced, which is an additional economic benefit. On the other hand, in small islands only when the demand of the system is high, the frequency response improves if wind turbines provide frequency regulation. Given its smaller size, each unit produces a high percentage of the total demand, and therefore, the outage of one of them has a considerable impact on the frequency response of the entire system.

Although RES providing frequency regulation might be expected to always improve the frequency response of the system at first glance, results show that deloading wind power is not advisable for low wind penetration scenarios. Considering future scenarios where the demand of the system will increase and, given the tendency of operators of Spanish island to reduce thermal generation in the future and add more RES, the results suggest that providing frequency regulation and reserve provision by wind generators is recommendable to improve the frequency response of the system and to reduce the total operation costs. In small islands, enabling wind generators to provide frequency violation is not urgent in terms of improving the frequency response, given that the benefits will appear when the demand increases in the up-coming years. For bigger islands like Tenerife, benefits can immediately appear if wind turbines were able to provide frequency regulation with the appropriate deloading factor.

It can also be concluded that under the current practice of system operators that implement UC models that schedule a minimum amount of reserve irrespective of dynamic behaviour of units, in order to foster the deployment of RES in future demand scenarios, it is essential to implement a fixed deloading percentage of RES in wind generators and not a variable deloading decided by the UC in order to improve dynamic performance of the system. This consideration would reduce the magnitude and expected cost of UFLS. A variable deloading factor is not advisable since it is determined by a UC neglecting frequency behaviour and worsens the overall dynamic behabiour of certain scenarios with respect to a fixed deloaded factor.

It seems also interesting that, in order to capture both the minimum system cost and the best dynamic behaviour, real systems should move to the use of unit commitment models that include frequency related constraints.

The methodology used in this work has proven to be very complete. However, it is noticeable that the UFLS schemes that have been used will change for future scenarios, therefore more research should be done in this aspect to provide more reliable and realistic results.

Future research will tackle the analysis of the frequency response under future optimal UFLS schemes and will find the variable deloading factor that achieves optimal results both in the frequency response and economically by considering technical constraints in the economic dispatches.

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ANNEX A: SIMULINK MODEL

The Simulink model used for the simulations is the following:

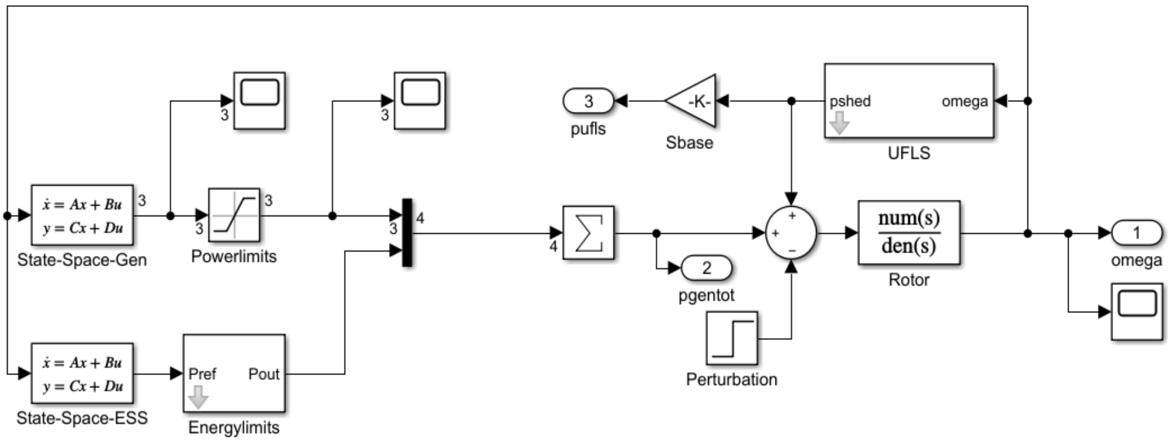

Fig. 18. System Frequency Dynamics model in Simulink.

ANNEX B: WIND PARAMETERS

The data sheet of the wind unit used in every simulation run is the following:

Bus	**WIND**
k (on MBASE, =1/R)	20.00
H (s) (on MBASE)	0.00
Pmin (MW)	0.00
B1	2.00
B2	0.00
A1	0.01
A2	0.00

Table X. Wind data sheet.

ANNEX C: UNDERFREQUENCY LOAD SHEDDING SCHEMES

- ***Tenerife***

The current UFLS schemes used for Tenerife are the following:

Type	Substation	Frequency (Hz)	ROCOF (Hz/s)	Int. delay (s)	Open. delay (s)	load (%)
uf	1	49.00		0.10	0.20	0.32
uf	2	49.00		0.10	0.20	0.23
uf	3	49.00		0.10	0.20	0.72
uf	4	49.00		0.10	0.20	0.63
uf	5	49.00		0.10	0.20	0.60
uf	6	49.00		0.10	0.20	0.48
uf	7	49.00		0.10	0.20	0.46
uf	8	48.92		0.15	0.20	0.65
uf	9	48.92		0.15	0.20	0.83
uf	10	48.92		0.15	0.20	0.98
uf	11	48.92		0.15	0.20	0.60
uf	12	48.92		0.15	0.20	0.64
uf	13	48.92		0.15	0.20	0.45
uf	14	48.92		0.15	0.20	0.95
uf	15	48.92		0.15	0.20	0.17
uf	16	48.85		0.20	0.20	0.87
uf	17	48.85		0.20	0.20	0.26
uf	18	48.85		0.20	0.20	0.69
uf	19	48.85		0.20	0.20	1.02
uf	20	48.85		0.20	0.20	0.61
uf	21	48.85		0.20	0.20	0.66
uf	22	48.85		0.20	0.20	0.73
uf	23	48.85		0.20	0.20	0.20
uf	24	48.79		0.30	0.20	1.02
uf	25	48.79		0.30	0.20	0.05
uf	26	48.79		0.30	0.20	0.67
uf	27	48.79		0.30	0.20	0.60
uf	28	48.79		0.30	0.20	1.30
uf	29	48.79		0.30	0.20	1.09

uf	30	48.79		0.30	0.20	0.95
uf	31	48.72		0.40	0.20	0.36
uf	32	48.72		0.40	0.20	0.98
uf	33	48.72		0.40	0.20	1.10
uf	34	48.72		0.40	0.20	1.29
uf	35	48.72		0.40	0.20	0.45
uf	36	48.66		0.50	0.20	0.89
uf	37	48.66		0.50	0.20	0.59
uf	38	48.66		0.50	0.20	0.28
uf	39	48.66		0.50	0.20	0.99
uf	40	48.66		0.50	0.20	0.97
uf	41	48.66		0.50	0.20	0.91
uf	42	48.66		0.50	0.20	0.64
uf	43	48.66		0.50	0.20	1.13
uf	44	48.66		0.50	0.20	0.99
uf	45	48.66		0.50	0.20	0.97
uf	46	48.66		0.50	0.20	1.15
uf	47	48.66		0.50	0.20	0.44
uf	48	48.60		0.60	0.20	1.17
uf	49	48.60		0.60	0.20	0.68
uf	50	48.60		0.60	0.20	0.69
uf	51	48.60		0.60	0.20	0.78
uf	52	48.60		0.60	0.20	1.39
uf	53	48.60		0.60	0.20	0.76
uf	54	48.55		0.70	0.20	0.01
uf	55	48.55		0.70	0.20	0.56
uf	56	48.55		0.70	0.20	0.71
uf	57	48.55		0.70	0.20	1.07
uf	58	48.55		0.70	0.20	0.70
uf	59	48.50		0.80	0.20	0.23
uf	60	48.50		0.80	0.20	0.58
uf	61	48.50		0.80	0.20	0.44
uf	62	48.50		0.80	0.20	0.46
uf	63	48.50		0.80	0.20	0.98
uf	64	48.50		0.80	0.20	0.97
uf	65	48.50		0.80	0.20	0.08
uf	66	48.50		0.80	0.20	0.32
uf	67	48.35		0.90	0.20	0.12
uf	68	48.35		0.90	0.20	0.79
uf	69	48.35		0.90	0.20	0.79
uf	70	48.35		0.90	0.20	0.75

uf	71	48.35		0.90	0.20	0.41
uf	72	48.35		0.90	0.20	1.13
uf	73	48.35		0.90	0.20	0.90
uf	74	48.35		0.90	0.20	1.01
uf	75	48.00		1.00	0.20	0.83
uf	76	48.00		1.00	0.20	0.26
uf	77	48.00		1.00	0.20	0.91
uf	78	48.00		1.00	0.20	0.70
uf	79	48.00		1.00	0.20	0.15
uf	80	48.00		1.00	0.20	0.45
uf	81	48.00		1.00	0.20	0.40
uf	82	48.00		1.00	0.20	0.64
uf	83	48.00		1.00	0.20	0.78
uf	84	48.00		1.00	0.20	1.15
uf	85	48.00		1.00	0.20	0.75
uf	86	48.00		1.00	0.20	0.43
uf	87	48.00		1.00	0.20	0.77
uf	88	48.00		1.00	0.20	0.65
uf	89	48.00		1.00	0.20	0.41
uf	90	48.00		1.00	0.20	1.07
rocof	27	49.30	-0.80	0.15	0.20	0.60
rocof	28	49.30	-0.80	0.15	0.20	1.30
rocof	29	49.30	-0.80	0.15	0.20	1.09
rocof	30	49.30	-0.80	0.15	0.20	0.95
rocof	24	49.30	-0.80	0.15	0.20	1.02
rocof	25	49.30	-0.80	0.15	0.20	0.05
rocof	26	49.30	-0.80	0.15	0.20	0.67
rocof	34	49.30	-0.80	0.15	0.20	1.29
rocof	35	49.30	-0.80	0.15	0.20	0.45
rocof	22	49.30	-0.80	0.15	0.20	0.73
rocof	23	49.30	-0.80	0.15	0.20	0.20
rocof	8	49.30	-0.80	0.15	0.20	0.65
rocof	10	49.30	-0.80	0.15	0.20	0.98

Table XI. UFLS schemes in Tenerife.

- ***La Palma***

The current UFLS used for la Palma are the following:

Type	Substation	Frequ (Hz)	ROCOF (Hz/s)	Int. delay (s)	Open. delay (s)	load (%)
uf	2101	48.81		0.30	0.20	6.00
uf	2102	48.81		0.60	0.20	0.40
uf	3101	48.66		1	0.2	10.5
uf	3102	48.66		1.5	0.2	3.8
uf	2103	48.66		2	0.2	7
uf	1101	48.00		0.80	0.20	17.40
uf	1111	48.00		1.50	0.20	8.70
uf	3103	47.00		1.80	0.20	12.30
uf	3104	47.00		2.10	0.20	11.50
uf	1102	47		2.4	0.2	2.2
uf	1112	47		2.4	0.2	7.8
rocof	2101	49.5	-1.8	0.1	0.2	6
rocof	21020	49.5	-1.8	0.1	0.2	0.4
rocof	3101	49.3	-1.8	0.1	0.2	10.5
rocof	3102	49.3	-1.8	0.1	0.2	3.8

Table XII. UFLS schemes in La Palma.

ANNEX D: SUSTAINABLE DEVELOPMENT GOALS

The 2030 Agenda for Sustainable Development are 17 global goals that aim to reduce inequalities, end poverty, and promote sustainability and prosperity in the world. They were adopted by all United Nations member states in 2015 and great efforts have been taking place to achieve them.

This Final Degree Project is mainly aligned with Sustainable Development Goal number 7 (Affordable and clean Energy), with number 11 (Sustainable cities and communities) and number 13 (Climate Action).

SDG Dimenssion	**SDG Identified**	**Role in the project**
Society	SDG 7: Affordable and Clean Energy	Primary
Society	SDG 11: Sustainable Cities and Communities	Secondary
Biosphere	SDG 13: Climate Action	Secondary

Table XIII. Sustainable Development Goals

- ***SDG 7: AFFORDABLE AND CLEAN ENERGY***

SDG 7 highlights the increasing energy demand that has been taking place in the recent decades, and which is expected to keep growing in the up-coming years as a result of global population growth. It emphasizes the importance of clean, efficient and non-pollutant energy generation as the main source of the global future energy mix, which is now set to a 17%

share in the total energy consumption. It also establishes as a goal for 2030 universal access to affordable, secure and innovative electricity services as well as an increasement in the total share of renewable generation by prioritizing its use, improving its infrastructure and optimizing the technology implemented. Many efforts have already been made in this area worldwide, but there is still a lot to be achieved. In fact, the COVID-19 outbreak has made it clear that it is critical for health facilities to have affordable and reliable energy, since 1 out of 4 buildings are not electrified. [1]

This Final Degree Project contributes to this SDG by proposing a greater penetration of non-pollutant energies and, in particular, of wind energy, and a decrease in fossil fuel and conventional thermal generation units, improving the profitability of the system and following energy efficiency criteria.

Results have shown that by year 2030, a full renewable of supply of the demand could be achieved in islands power systems of all sizes. As this work can be extrapolated to islands worldwide, full renewable supply of the demand in this power systems could be reached within less than 10 years. Since approximately 11% of the world's total population (730 million people) lives in islands, the positive environmental impact would be considerable.

In Spain, around 7.2% of the total population (3.41 million people) who live in islands could be supplied with clean and renewable energy by 2030. Because of the scarcity of energy resources, the country's energy sector constitutes approximately 2.5% of the GDP.[2]

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[1] Y. Sokona, "Advancing the 2030 Agenda: Interlinkages and Common Themes at the HLPF 2018 SDG 7: Ensuring access to affordable, reliable, sustainable and modern energy for all."

[2] "Summary of the Commission assessment of the draft National Energy and Climate Plan 2021-2030 SPAIN-National targets and contributions foreseen in the draft National Energy and Climate Plan."

The aim of Spanish operators is to increase the share of renewable energies in the region. In 2019 has increased by a 14%, and it is expected to reach a 42% by 2030.[3]

In addition, a greater guarantee of security and continuity of supply can be achieved, thus reducing the possibility of load shedding to consumers. By 2030, the total cost of load shedding could be reduced by more than 50% in islands of all sizes. As a result, the proportion of population with access to electricity could be increased and less black outs would take place worldwide.

- ***SDG 11: SUSTAINABLE CITIES AND COMMUNITIES***

SDG 11 has as one of its targes to reduce the negative environmental impact of cities, creating a healthier environment and therefore improving the quality of life of the inhabitants.

Among others, it highlights the importance of improving the air quality, as it has caused more than 4.2 million premature deaths only in 2016. It also warns out about waste management in urban spaces. [4]

Results from this work show that enabling renewable energy sources to participate in the reserve and frequency regulation of island power systems can result in a full renewable supply of the demand in these power systems by year 2030, which would reduce the total amount of thermal generation produced in islands worldwide.

This would save more than 1800 kilotons gasoil, diesel oil and fuel oil only in the Canary Islands[5], so the impact considering the potential reach of this project makes this mechanism

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[3] “Renewable Hydrogen Roadmap Hydrogen Energy Network (HyENet),” 2020.

[4] “Goal 11 Make cities and human settlements inclusive, safe, resilient and sustainable.”

[5] Consejería de Transición Ecológica Lucha contra el cambio climático y Planificación Territorial, “Anuario energético de Canarias 2018,” p. 329, 2019.

very interesting in order to evolve towards a smart and efficient electrical grid as well as to decrease the total waste that result from the use of conventional thermal generation. Consequently, the total amount of gas emissions would be reduced, and the air quality would improve.

- ***SDG 13: CLIMATE ACTION***

SDG 13 highlights the effect of climate change and the catastrophic consequences it entails. Greenhouse gas emissions have risen by 50% since 1990 and global warming has already taken an important issue to be considered on the planet, increasing global temperatures and sea levels among other effects. [6]

This project contributes to this SDG by aiming the decarbonization of islanded systems, thus reducing the emission of polluting gases. In particular, since the islands of study (La Palma and Tenerife) are representative of a high number of islands worldwide, to consider a deloading factor in wind power turbines could lead to a reduction of gas emissions on a large scale.

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[6] “Goal 13 | Department of Economic and Social Affairs.” https://sdgs.un.org/goals/goal13 (accessed May 30, 2021).