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Techno-economic assessment of increasing the renewable energy supply in the Canary Islands: The case of Tenerife and Gran Canaria

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A B S T R A C T

The Canary Islands power systems face environmental, economic, and social sustainability challenges. They heavily rely on imported fossil fuel for electricity generation; this leads to an increase in the Cost of Electricity (COE) and CO_2 emission; a reduction can be made by utilizing more renewable energy sources (RES). This paper presents a comprehensive techno-economic assessment of increasing the RES utilization in Tenerife and Gran Canaria. Results illustrate that the least-cost RES penetration in each island exceeds 60% compared to 18.8% and 15.5% today. This implies a potential 58% reduction in CO_2 emission intensity. The additional RES integration decreases the COE by 23.0% and 25.3% in Tenerife and Gran Canaria, respectively. The impact of imposing CO_2 emission penalties is explored, results show a slight increase in the optimal RES capacity. Electrical Interconnection between both islands is also investigated, it is found to increase the optimal aggregate RES penetration beyond 70%, reduce COE by 30.3% and lower CO_2 emission by 70%, compared to the current situation. Finally, the results obtained can support decision-makers to establish policies to help transform the energy system in islands into a more sustainable and reliable system using RES, energy storage, and energy exchange between islands.

1. Introduction

Electricity is an essential service to citizens' economic and social activities across any society, and the power generation sector is considered the main block for the electricity's energy chain. An approach for electricity generation in islands is using thermal generation, which depends on importing fossil fuels from external territories (Cross-Call, 2013). This situation imposes challenges on islands to meet their energy demand sustainably and economically. The high cost of transporting fossil fuel due to the isolated geographical location and the small amount of purchased quantities can significantly increase the fuel costs (Cross-Call, 2013; Sigrist et al., 2017). Furthermore, the environmental impact associated with fossil fuels is high. In recent years, several policies have been established to reduce CO_2 emissions by transforming the current energy systems into more sustainable energy supplies on a large scale. The European Union (EU) has promoted a set of targets to mitigate climate change and other energy-related issues by 2050 and initiated several programs to support clean energy usages in EU islands, such as The Clean Energy for EU Islands initiative launched in 2017 ("Clean Energy for EU Islands Secretariat," n.d.), the Smart Island Initiative and Valletta Declaration (Groppi et al., 2021). The policies focus on energy security, vulnerability and sustainable energy generation (European Commission, 2014). In addition, the EU encourages outermost regions islands, such as the Canarias Islands, to transition to a more sustainable electrical power system (Maldonado, 2017).

The Canary archipelago consists of seven islands Tenerife, Fuerteventura, Gran Canaria, Lanzarote, La Palma, La Gomera and El Hierro. The archipelago is located in the Atlantic Ocean, about 150 km off the northwest coast of Africa and around 1350 km from mainland Europe (Dallavalle et al., 2021; Ramos-Real et al., 2018). The population is mainly concentrated in two islands, Tenerife (949,471) and Gran Canaria (865,756), collectively exceeding 82% of the Canary population (European Commission, 2019). The climate in the islands is subtropical, with long and hot summers and moderately warm winters (NASA Prediction Of Worldwide Energy Resources, n.d.).

46% of Spain's total primary energy supply was from liquid fuels in 2016, primarily imported fossil fuels, which in 2016 was around 1.3 million barrels per day of oil and 932 billion cubic feet of natural gas (U. S. Energy Information Administration, 2017). External energy dependency in the Canary Islands is even higher than in the mainland, as ~85% of their electricity is from thermal generation relying on fossil

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Abbreviations

BaU	Business as Usual
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
CO	Carbon Monoxide
COE	Cost of Electricity generation
CC	Cycle-Charging
DoD	Depth of Discharge
EU	European Union
HVDC	High Voltage Direct Current
LCOE	Levelized Cost of Energy
LF	Load Following
NPC	Net Present Cost
NO_X	Nitrogen Oxides
OPEX	Operating Expenses
PM	Particulate Matter
PV	Photovoltaic
REE	Red Eléctrica de España
RES	Renewable Energy Sources
SO_2	Sulfur Dioxide
UHC	Unburned Hydrocarbons

fuels (Gobierno de Canarias, 2020; Maldonado, 2017; Ramos-Real et al., 2018; Santamarta et al., 2014). Hence, even though solar and wind resources are abundantly present, their relative electricity generation share remains low at ~15%. Due to their location off the northwest coast of Africa, it is extremely challenging to connect the islands to the Spanish peninsula's primary power grid. Hence, the electrical system of the islands can be mainly characterised as a group of small and isolated systems, increasing the overall cost of electricity generation. The average cost of electricity generation in 2019 in the Canary Islands was 0.152 €/kWh compared to 0.129 €/kWh in the Balearic Islands and 0.0532 €/kWh in the Spanish mainland (Gobierno de Canarias, 2020; OMI Polo Español S.A. (OMIE), 2019).

The government in Spain aims to increase RES penetration on the Spanish islands to decrease the generation cost (BloombergNEF, 2020; Red Eléctrica de España, n.d.). Also, to align with different EU initiatives (European Commission, 2020). The current energy policy in the Canary Islands focuses on developing a new energy model based on renewable energy based on the following key actions (Red Eléctrica de España, n.d.):

- Build a new infrastructure to facilitate the integration of renewable energy.
- Develop new interconnections between islands, reducing power system's generation cost and increasing RES penetration (Lobato et al., 2017).
- Integrate energy storage systems to balance the intermittency of an increased energy generation mix based on RES. The fluctuations in the generated energy by the RES and lower capacity factors comparing them with the fossil fuel technologies, the storage system provides flexibility and stability for the system, it stores energy when there is a generation surplus and meet the demand when RES are not able to provide the required amount of energy for the load. Also, to meet the voltage and frequency requirements of the power system (Blanco and Faaij, 2018).

1.1. Literature review

Several articles studied the possibility of using renewable power systems for remote Islands, those studies aim to propose innovative energy solutions to reduce electricity generation cost, environmental cost and develop a more reliable and sustainable power system in the islands (Cross et al., 2017; He et al., 2021; Tróndheim et al., 2021). Many articles focused on the Canary Islands as a case due to it is location, relatively high population and a high potential for renewable energy (Barone et al., 2021; Dallavalle et al., 2021; Gils and Simon, 2017; Marrero and Ramos-Real, 2010; Ramos-Real et al., 2018). A study (Schallenberg-Rodriguez, 2014) evaluated the usage of PV in roofs of houses in the Canary Islands, the COE in Gran Canaria was found to be 0.087 €/kWh and 0.083 €/kWh in Tenerife. However, the study did not obtain the COE with energy storage and integration with the grid added to the PV roof system. Authors in (Dallavalle et al., 2021) proposed a hybrid power system based on wave and solar energy. The study assessed the economic and the technical side of the hybrid system. The LCOE of solar energy was 54 €/MWh and 261 €/MWh for wave energy. Another study (Cabrera et al., 2018) investigated the increase of different types RES in Gran Canaria, the study accomplished RES of 75.9% that can be implemented at the present time. In addition, the study showed that a 100% RES penetration in the Canary Islands could be achieved in the future.

Electric interconnections between islands are broadly installed all over the world to connect different power systems, it is used between islands via submarine cables to provide several benefits for islands with isolated power systems, such as improved reliability and sustainability, reduced cost, improved system efficiency (Alves et al., 2019; Kaldellis and Zafirakis, 2007; Lobato et al., 2017) and increased RES penetration (Eras-Almeida et al., 2020; Lobato et al., 2017). Several techno-economic studies show the impact of islands interconnection on increased penetration of RES in different regions of the world, such as Greece (Georgiou et al., 2011; Zafeiratou and Spataru, 2017), the Philippines (Agua et al., 2020), Ecuador (Eras-Almeida et al., 2020) and Spain (Lobato et al., 2017). One interconnection has been implemented between Fuerteventura and Lanzarote. Another interconnection is under construction between Tenerife and La Gomera with a capacity of 50 MVA and a length of 36 km (Red Eléctrica de España, 2021a). Fuerteventura and Lanzarote interconnection has been studied in (Lobato et al., 2017), the study analysed the interconnection between different sets of islands in Spain, the entire Balearic archipelago and Lanzarote-Fuerteventura in the Canary archipelago. Results indicated that interconnections contributed to each island's total energy reserve by allowing them to share energy among themselves. Therefore, thermal units worked more efficiently and economically. However, the study observed that the financial benefit of interconnection between the islands depends on their characteristics. Some studies have presented other possible interconnections between the Canary Islands (Gils and Simon, 2017; Ramos-Real et al., 2018). The work in (Ramos-Real et al., 2018) demonstrated the economic and environmental impacts of the interconnection between Tenerife and La Gomera in terms of energy independence, CO_2 emissions and costs, the paper presented four scenarios with interconnection between the two islands. The scenarios examined the different types of fuel used for generation (oil-based fuel or natural gas) and the availability of energy storage systems. The study concluded that the electrical interconnection between the islands is the best option in the long term when natural gas is used as an alternative fuel. Furthermore, the RES share increased between 30% and 40% for the interconnection cases compared to the base case where no interconnection between islands is present. Moreover, the CO_2 emissions are reduced by 46% compared to the base case. Another work (Gils and

Simon, 2017) presented a road map to have 100% renewable energy supply for the Canary Islands by 2050. The proposed system suggested the interconnection between all islands of the Canary archipelago enable a reduction in supply cost by 15% and balancing of RES fluctuations. Additionally, the work that has been published in 2017 suggested to double the wind installations and triple the photovoltaic (PV) installations by 2020 and double again wind and PV installations in 2025 to reach 100% renewable energy generation in 2050.

1.2. Aim and scope

The literature review indicates a limited number of existing studies focused on the interconnection between islands in the Canary archipelago. The existing studies either cover the interconnection between a large island and a small island in the Canary islands as in (Ramos-Real et al., 2018) and (Lobato et al., 2017) or the interconnection in general between all the Canary Islands (Gils and Simon, 2017). On the other hand, this work aims to optimize the electricity system in Tenerife and Gran Canaria in the Canary archipelago with higher penetration of photovoltaic and wind sources while achieving low emission targets using multiple scenarios, including isolated islands operation and interconnection between the two islands. The work focuses on PV and wind sources instead of other potential RES such as geothermal and Concentrating Solar Power (CSP) is justified as follow: The financial risk is lower for PV and wind because of the amount of research and projects that have been done in those two technologies compared to geothermal where financial risk is high and prediction of the quality of a resource requires capital investment in drilling and well tests. In addition, the absence of regulation for geothermal increases the financial risk (Colmenar-Santos et al., 2018). The COE of utility-scale RES in 2020 for PV is lower than CSP 0.057 $/kWh compared to 0.108 $/kWh (IRENA, 2020). Also, the current system in the islands is already using PV and wind. Thus, the system's expansion can be done with minimum technical and regulations issues.

The work aims to fill this research gap using least-cost optimization, allowing the authors to evaluate the interconnected and non-interconnected cases in more detail by comparing COE and CO_2 emission intensity in different scenarios. Lastly, the paper quantitatively supports the key actions suggested by Red Eléctrica de España and the EU for the Canary Islands (European Commission, 2020; Hernandez et al., 2017; Red Eléctrica de España, n.d.). To achieve the proposed strategy, the authors investigate four scenarios, two scenarios deal with each island independently (non-interconnected) and the rest of the scenarios are with electrical interconnection between Tenerife and Gran Canaria. The first scenario models the electrical system reported by (Gobierno de Canarias, 2020) in 2019 for Tenerife and Gran Canaria. The second scenario increases the RES penetration and battery storage in each island to achieve an optimal COE. The third scenario remodels scenario 1 but with interconnection between both islands. Finally, the RES penetration is increased in the fourth scenario while the interconnection is introduced. The paper is organized as follows: Section 2 provides a brief overview of the current power system in the Canary Islands, Section 3 details the four scenarios in terms of technical, economic and simulation assumptions. Also, the section presents the modelling method used in this work. The results and discussion for the four scenarios are presented and discussed in Section 4. Finally, conclusions and policy implications are drawn in Section 5.

2. Overall of the power system in the Canary Islands

Table 1 provides an overview of the power system already implemented in each of the Canary Islands (Gobierno de Canarias, 2020). The RES provide only 15.9% of the generated electricity in the archipelago, where the highest RES capacity share is in El Hierro island, which is 60.6%. However, the total generation in El Hierro is only 0.7% of the archipelago generation. The lowest island in RES installation is La Gomera with only 0.4 MW, 90% of the RES installations in La Gomera are wind turbines. The most populated two islands in the archipelago (Tenerife and Gran Canaria) generate 81.2% and 84.5% of their electricity from thermal generation, respectively. Therefore, both islands produce the highest CO_2 emissions in the archipelago, the two islands make 76.7% of the CO_2 emissions in the archipelago. The rest of the energy in Tenerife and Gran Canaria is generated from RES, mainly solar and wind energy. Wind energy contributes to 13.3% and 13.9% of the total generated electricity in Tenerife and Gran Canaria.

On the other hand, solar energy provides only 5.1% and 1.5% of the generated electricity in Tenerife and Gran Canaria. Other RES types such as hydroelectric and biogas are used in the archipelago but in limited capacitates, El Hierro is the only island that produces energy from hydroelectric with an installed capacity of 22.8 MW. Also, biogas is used in Lanzarote island with a capacity of 2 MW. These numbers show that further RES installation can help to reduce CO_2 emissions and have a more sustainable energy supply with less dependence on imported fuel to generate electricity.

The hourly peak demand for the archipelago in 2019 was 1371.84 MW and the energy consumption per capita in the Canary Islands was 4121 KWh/capita in 2019 compared to 5626 KWh/capita in the Spanish Peninsula as reported by (Gobierno de Canarias, 2020). In terms of electrical interconnection between islands, only one interconnection operates between Fuerteventura and Lanzarote. The interconnection contributes to reducing the operating costs through the use of the thermal units in a more efficient approach (Lobato et al., 2017).

One year load profile with an hourly frequency (8760 points) for Tenerife and Gran Canaria has been extracted from aggregated Canary islands' load consumption data from 2019. The profile is based on the generation capacity proportion of these islands compared to the other Canary Islands (Red Eléctrica de España, 2021), the capacity ratio between each island and the total installed capacity is found. Then the aggregated hourly demand is divided by the percentage calculated for each island to obtain the hourly demand proportion estimate for the

Table 1
The power system details for the Canary Islands (Year, 2019).

	Tenerife	Gran Canaria	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Total
Total Generation (MWh)	**3,710,951**	**3,581,933**	**906,078**	**716,839**	**281,016**	**76,850**	**62,430**	**9,336,098**
Thermal Generation (MWh)	3,014,854 (81.2%)	3,028,053 (84.5%)	826,454 (91.2%)	636,732 (88.8%)	251,935 (89.7%)	76,696 (99.8%)	20,738 (33.2%)	7,855,463 (84.1%)
RES Generation (MWh)	696,097 (18.8%)	553,880 (15.5%)	79,623 (8.8%)	80,108 (11.2%)	29,081 (10.3%)	154 (0.2%)	41,692 (66.8%)	1,480,635 (15.9%)
Total Installed Capacity (MW)	**1428.5**	**1228.4**	**266.8**	**229.8**	**118.4**	**21.6**	**37.8**	**3331.3**
Thermal Capacity (MW)	1111.6 (77.8%)	1024.1 (83.4%)	232.4 (87.1%)	187.0 (81.4%)	105.3 (89%)	21.2 (98.1%)	14.9 (39.4%)	2696.5 (80.9%)
RES Capacity (MW)	316.9 (22.2%)	204.3 (16.6%)	34.4 (12.9%)	42.8 (18.6%)	13.1 (11%)	0.4 (1.9%)	22.9 (60.6%)	634.8 (19.1%)
Produced CO_2 Emissions (tCO_2)	2,119,442	2,065,132	549,592	482,643	171,820	52,844	14,268	5,451,691

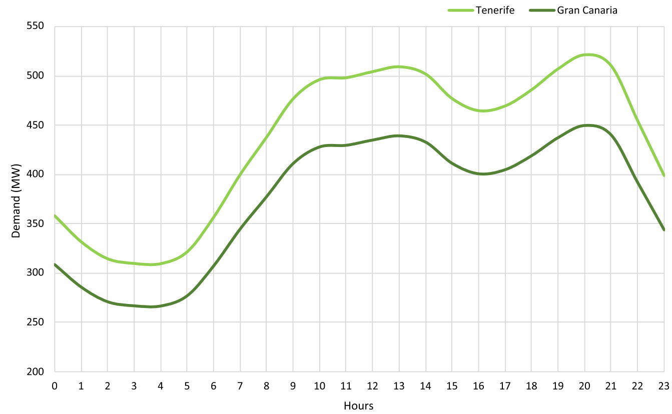

Fig. 1. Hourly electricity load of Tenerife and Gran Canaria at maximum daily demand in 2019 (17-10-2019) based on data available in (Gobierno de Canarias, 2020).

desired island. The Maximum hourly demand is 588.1 MW and 506.5 MW, with a daily average of 10.4 GWh and 8.9 GWh for Tenerife and Gran Canaria, respectively. The hourly demand on the October 17, 2019 between both islands is similar, according to Fig. 1. The peak demand on this day took place around 21:00, while the lowest demand occurred around 04:00.

3. Methodology

This section describes the basic principles and proposed methods used to achieve the aim of this paper. Four scenarios are investigated in this article as shown in Fig. 2.

- Scenario (S1): BaU (current situation) simulation for each island independently based on the information available from (Gobierno de Canarias, 2020). This scenario is simulated to identify the actual cost of electricity supply in 2019 for Tenerife and Gran Canaria.
- Scenario (S2): Increases the RES penetration in each island under different CO_2 emissions penalties (0 €/ton, 30 €/ton and 60 €/ton). In this scenario, the RES share is optimally increased by adding new RES and battery storage systems to the existing power system to achieve higher RES penetration than the BaU with the optimal COE. Furthermore, this scenario investigates a range of CO_2 penalties and their effect on COE and produced CO_2 emissions.
- Scenario (S3): Creates an interconnection between Tenerife and Gran Canaria BaU models. A subsea HVDC interconnection cable is proposed to unlock the ability of power exchange between the two islands.
- Scenario (S4): Increases the RES penetration with the interconnection between Tenerife and Gran Canaria. Based on S3 model, new installations of RES and battery storage are introduced and optimized to achieve the optimal COE.

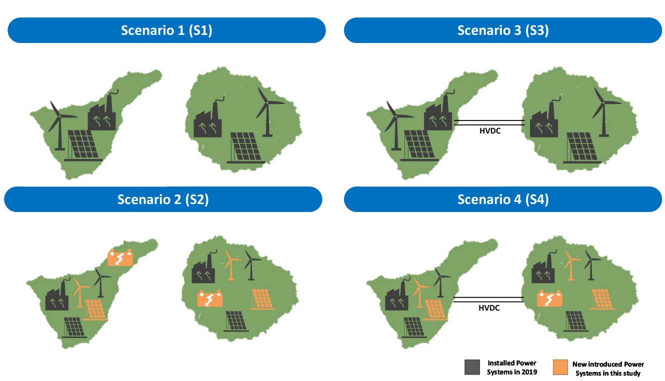

Fig. 2. An illustration of the proposed scenarios in this study. **S1:** BaU (current situation) for each island independently, **S2:** Increase the RES penetration in each island, **S3:** the current RES penetration with electrical interconnection, **S4:** Increase the RES penetration in each island with electrical interconnection.

3.1. Modelling software

All scenarios considered are modelled using the HOMER software. HOMER simulates the operation of a system by making energy balance calculations in each time step of the year. HOMER is commonly used for least-cost optimization in different stand-alone or grid-connected microgrids case studies (Agua et al., 2020; Ellabban and Alassi, 2021; Eras-Almeida et al., 2020; Kumar et al., 2019; Montuori et al., 2014). It has been used in several studies for techno-economic assessments and sensitivity analysis studies because it can model different microgrid configurations as the software includes various generation resources, such as fossil fuel generators, PV, wind, biomass and hydro systems. It also contains multiple energy storage technologies, such as battery storage, hydrogen storage and supercapacitors. HOMER provides an indication of the environmental impact by determining the emissions produced from the power system. It calculates the emissions of CO_2, CO, UHC, PM, SO_2 and NO_X by assessing the proportion of each pollutant in the fuel and multiplying them by the total annual fuel consumption. In addition, emissions' penalties can be applied for the modelled system as an optimization input. HOMER adds the cost of emissions to the total annual cost of the power system (HOMER Energy, 2020).

This paper uses COE or LCOE as merit to assess, compare, and rank the different proposed scenarios. It is used as a standard to determine the cost-effectiveness of a given scenario. The COE is the average cost of electricity per kWh of useful electrical energy produced by the system, calculated on annualized generation cost and load basis. The COE parameter is calculated using Equation 1 (HOMER Energy, 2020).

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{1}$$

where $C_{ann,tot}$ is the total annualized cost of the system (€/yr) and E_{served} is the total electrical load served in kWh. The $C_{ann,tot}$ can be calculated using Equation (2).

$$C_{ann,tot} = CRF(i, R_{proj})^{*} C_{NPC,tot} \tag{2}$$

where $CRF(i, R_{proj})$ is the capital recovery factor or discounting factor which is calculated using Equation (3) and $C_{NPC,tot}$ is the project's total Net Present Cost (NPC).

$$CRF(i, R_{proj}) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

where i is the real discount rate and N is the project's lifetime in years. NPC is another criterion used in this study to compare the various scenarios. NPC covers the installation of new systems, the annualized cost for the existing power system components, maintenance, operation, and replacement costs that occur over the project's lifetime.

Another parameter used in this work is the renewable fraction f_{ren}, shown in the equation below.

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{served}} \tag{4}$$

where E_{nonren} is the total non-renewable electrical production in a year (kWh/yr) and E_{served} is the total electrical load served in kWh/yr. This parameter is used to compare the optimized RES penetrations of the different scenarios. For CO_2 emissions evaluation, CO_2 emission intensity (g CO_2/kWh) is used to compare the various environmental aspects for the scenarios. This parameter is calculated as the ratio between CO_2 emissions (g) and gross electricity production (kWh).

3.2. Simulation parameters and models

The project lifetime is set to 25 years in this paper for economic benchmarking with an assumed real discount rate of 5.9%. However, the core optimizations are simulated for one year. HOMER offers two default dispatch strategies, load following (LF) and cycle-charging (CC). In LF dispatch method, generators produce power only to meet the load demand without charging any energy storage system, the RES charge the energy storage systems. On the other hand, CC serves the load demand and charges the battery storage system. In this work, LF dispatch method is used for sizing and cost optimization of the microgrids.

The islands' climatic information (temperature, irradiance and wind speed) are obtained from NASA satellites databases based on the geographical location. The yearly profile of GHI, clearness index and wind speed are shown in Fig. 3 (Top) for the Canary Islands. The figures are based on 8760 h profile (hourly profile) for GHI, clearness index and wind speed. It can be observed that daily irradiance is highest during the summer months while the lowest is in the winter months (Nov, Dec, Jan). Fig. 3 (Bottom) shows the monthly wind speed for the Canary Islands. The yearly average wind speed is calculated to be 7.5 m/s and the maximum speed is recorded in July, where the speed reaches 9.7 m/s.

Fig. 4 shows the HOMER models for the four scenarios proposed in this work. S1 and S2 are simulated using the fundamental blocks provided by the software. The load profile for each island is supplied alongside the cost and simulation assumptions. A limitation of HOMER is that it is unable to model two separate power systems in one simulation. An approach has been proposed in the literature to overcome this limitation and to model the interconnection between two separate systems, consisting of combining the load profile for each island into a single load profile and combining the generation alongside the RES capacities for both islands (Agua et al., 2020; Alves et al., 2019; Eras-Almeida et al., 2020). Despite the promising results obtained by the authors, the effect of interconnection is not presented in the technical analysis as no energy exchange boundary between the two systems exists. In addition, losses and efficiency of the interconnection are not considered in the reported results.

The interconnection impact on energy exchange is modelled here as follows: HOMER provides two buses for each model, one to allocate the AC loads and AC power system components and the other bus for DC load and DC power system components. Each island is represented as an electric bus, the AC bus is chosen to represent Tenerife island and the DC bus represents Gran Canaria. This approach helps in modelling each island separately while considering their energy exchange. The HVDC interconnection is modelled by the converter that connects the AC bus with the DC bus. HOMER allows the user to specify the capacity of the converter and the losses for the rectifier and inverter side. The converter capacity represents the HVDC interconnection capacity and the losses are modelled by the converter losses. Furthermore, the cost of the interconnection is added to the model as system fixed capital cost. In S4, the combined battery was installed in Gran Canaria as energy storage for both islands as HOMER is not able to simulate two batteries simultaneously. The final configurations for interconnection scenarios are presented in Fig. 4 (c) and (d).

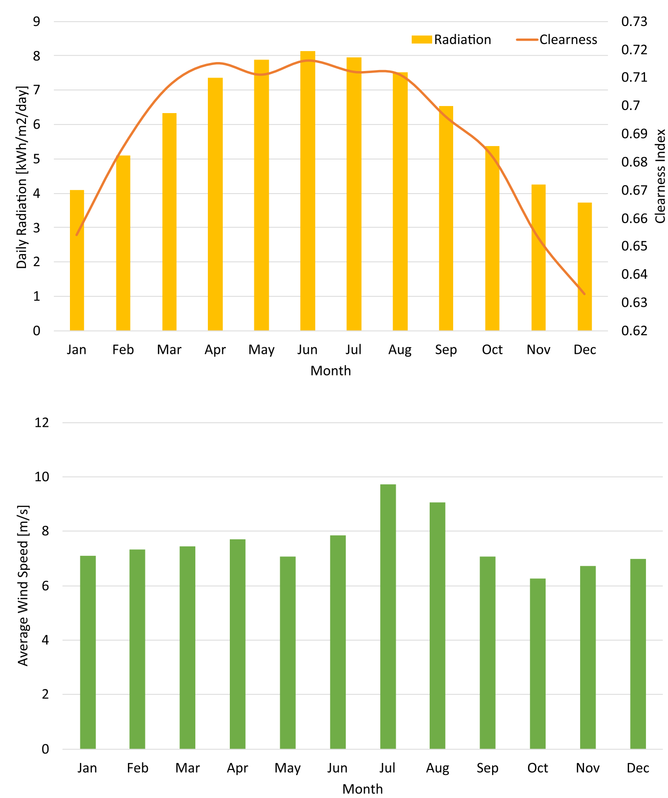

Fig. 3. The monthly average for the Solar GHI profile (Top) and wind speed profile (Bottom) for the Canary Islands.

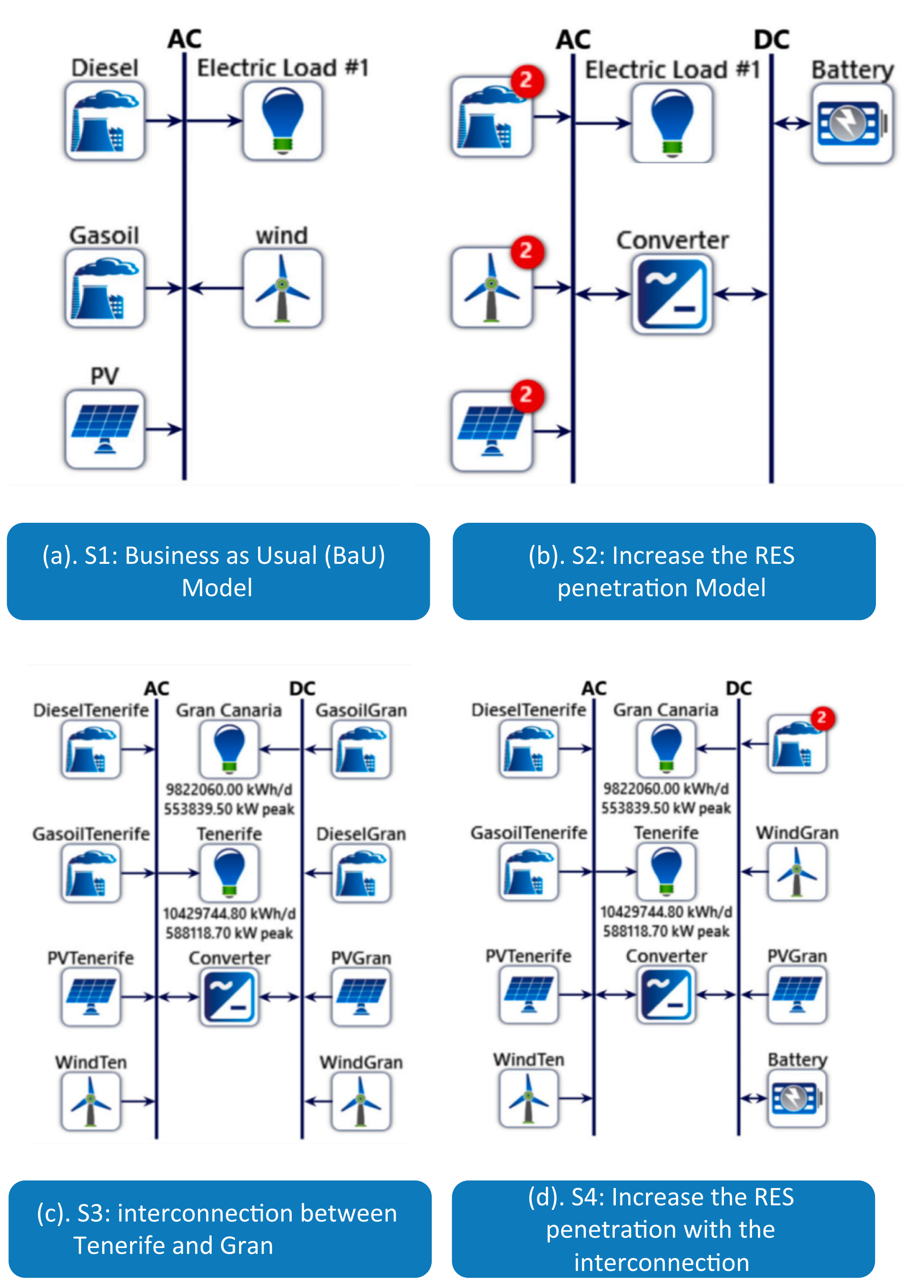

Fig. 4. Simulated models in HOMER for all proposed scenarios.

3.3. Technology and cost assumptions

The CAPEX and OPEX for the new installed technologies used in this study are demonstrated here as they will be considered in the simulation model. In addition, the CAPEX for the existing power system and generation stations (the system components built before 2019) is estimated by a factor so the value is reflected on the COE of all scenarios discussed in this work. Scenario 1 considers the pre 2019 CAPEX factor and OPEX for the existing power system and generation stations. In scenarios 2 and 4, the CAPEX of new RES and storage units is added to the correction factor of the BaU COE for both islands. Finally, scenarios 3 and 4 consider the interconnection CAPEX in their economic analysis.

3.3.1. Fuel-based generators and RES

The CAPEX and OPEX of the PV systems, wind turbines and battery storage systems have been estimated based on several local and international sources as shown in Table 2. The PV system, wind and storage CAPEX include the balance of system and power converters' costs. The fossil fuel's costs used in this work are obtained from the local Canary Islands report (Gobierno de Canarias, 2020). The prices are different between the islands due to the differing transportation cost. In Tenerife, gasoil price is 0.542 €/L and 0.495 €/L for diesel. On the other hand, the fuel cost is higher in Gran Canaria, which is stated to be 0.553 €/L for Gasoil and 0.506 €/L for diesel. For the BaU cases, several technical assumptions are applied to the simulation model. The wind turbine losses have been assumed to be 12.5% with average turbine heights of 70 m and 80 m for Tenerife and Gran Canaria, respectively. PV modules

Table 2
Economic and financial parameters for power system components.

Power System	CAPEX	OPEX	Ref
Fuel Generators	0 (€/kW)	0.0035 (€/op. hr/kW)	(U.S. Energy Information Administration, 2020)
Wind Turbine	1,593,000 (€/MW)	27,000 (€/year/MW)	Lazard (2020)
PV Systems	900 (€/kW)	8.8 (€/Year/kW)	BloombergNEF (2020)
Battery Storage	350 (€/kWh)	3.5 (€/Year/kWh)	(Cole and Frazier, 2019; IRENA, 2019)

are assumed to have the default HOMER input for degradation factor of 80% and ground reflectance of 20% for both islands. The selected battery storage technology is Li-ion batteries with 95% DoD and roundtrip efficiency of 92%, the battery is replaced every 15 years with a cost of 150 €/kWh to reflect the declining storage system costs. The average thermal generation stations efficiency in Tenerife is stated to be 38.88% and 40.16% in Gran Canaria based on (Gobierno de Canarias, 2020) and the minimum load ratio is stated to be 15% which is used to determine the reserve constraints and operating reserve. The CO_2 penalties are considered based on historical data as sensitivity inputs, the highest penalty price was recorded on May 2021 at 50.5 €/ton (Buli et al., 2021). Thus, this work's sensitivity analysis penalty prices are 30 €/ton and 60 €/ton.

3.3.2. Islands interconnection

The initial cost of the interconnection for scenarios 3 and 4 is calculated through an empirical formula derived by the authors based on data from commissioned HVDC projects. The project's data are obtained from a Bloomberg New Energy Finance (BNEF) dataset (Aspinall, 2016). A regression model is built using HVDC projects from the dataset for cost estimation. Several parameters were tested while building the model such as power rating, distance, voltage and commissioning year, and it is found that power and distance combination produces good model results with $R^2 = 0.85$. The model uses Cobb-Douglas economic function, with the historical costs adjusted for inflation. The presented formula in Equation (5) is observed to generate an average error of 27.8% against the actual costs based on 52 HVDC projects cost analysis.

$$C_{\$M} = 7.172\, P_{MW}^{0.5989} L_{km}^{0.1336} \tag{5}$$

Here, $C_{\$M}$ is the HVDC interconnection cost in millions of US \$, P_{MW} is the HVDC power rating in MW and L_{km} is the interconnection length in km. The distance between Tenerife and Gran Canaria islands interconnection points is estimated as 65 km using Google Earth. The interconnection capacity is selected close to the peak demand of Gran Canaria at around 500 MW. This assumption is confirmed through preliminary simulations indicating least-cost combined system cost at a similar capacity. Based on Equation (5), the proposed 500 MW interconnection cost is estimated at 518 million \$ (440 million €) (1€ = 1.179\$). This estimate is used as a base case for interconnection cost throughout this paper. Given the uncertainty associated with interconnection projects cost based on individual project circumstances, sensitivity analysis is carried out in section 4 to investigate the variable interconnection costs impact.

Finally, the total losses associated with the interconnection are calculated based on the available information in (Barnes et al., 2017; Sørensen, 2017). The converter substation losses are set as 1% and the cable losses are set as 0.4%/100 km (Keim and Bindra, 2017; May et al., 2016). The total losses for the proposed interconnection are thus set to 1.3%.

3.3.3. Pre 2019 installed system (S1) CAPEX estimation

Several literature review sources (Alves et al., 2019; Lobato et al., 2017) developed their economic models based on the assumption that the CAPEX of the current installed electrical system in the islands is zero. Therefore, it is not accounted for the economic analysis. This assumption will impact the financial analysis and the conclusions related to the COE/LCOE. The results will underestimate their values and will be challenging to compare the obtained with existing results. To provide more representative analysis and conclusions from this work, the current operated power system CAPEX is included in the economic models for all scenarios (S1 to S4). Given the difficulty of estimating the CAPEX of individual installed power stations at different points of time in the islands prior to 2019, the CAPEX of the existing power system needed is modelled in such a way to account for the different system components impact collectively. Accounting for this pre-analysis CAPEX helps to provide a realistic COE for the different proposed scenarios in this work.

A method is thus developed to estimate this CAPEX based on the published COE for the Canary Islands. As indicated earlier, the Canary Islands COE generation in 2019 is 0.152 €/kWh, and given that Tenerife and Gran Canaria represent more than 80% of the archipelago generation, this COE is considered here as their average, the individual COE is found for Tenerife to be 0.157 €/kWh and 0.146 €/kWh for Gran Canaria. Simulating the BaU scenario for both islands with zero CAPEX results into an underestimated COE compared to the published ones. Equation (6) is thus used and shows the details for the modified COE calculation for the BaU scenario, where the total annualized cost is divided into the known OPEX (mainly fuel prices and maintenance costs), and the unknown initial investment CAPEX.

$$COE_{canary} = \frac{AnnualizedCost_{OPEX} + AnnualizedCost_{CAPEX}}{Load} \tag{6}$$

By solving for annualized unknown CAPEX, Equation (6) is re-arranged to estimate the unknown CAPEX portion of the BaU scenario for each island, as in Equation (7), where the load value changes according to the considered island.

$$Annualized\ Cost_{CAPEX} = 0.152 * Load - Annualized\ Cost_{OPEX} \tag{7}$$

The obtained CAPEX value is then converted into NPC by multiplying it with the capital recovery factor (Equation (3)). Using this method, the CAPEX component for the existing system has been calculated to be 2300 million € for both islands and the CAPEX for Gran Canaria is 1000 million € and 1300 million € for Tenerife.

4. Results and discussion

4.1. Non-interconnected scenarios (S1, S2)

The BaU scenario (S1) input values were the power capacities of each technology installed on each island and the hourly load profile. The

Table 3
Comparison between the BaU Scenario simulation results and the actual generation values in 2019.

Energy Source	Tenerife			Gran Canaria		
	Actual Generation (MWh)	Simulation Results (MWh)	Error (%)	Actual Generation (MWh)	Simulation Results (MWh)	Error (%)
Diesel Generators	1,398,868	1,406,515	**0.55**	1,339,763	1,420,283	**6.01**
Gasoil Generators	1,629,185	1,627,910	**0.08**	1,675,091	1,707,138	**1.91**
Wind Turbines	498,435	495,377	**0.61**	495,251	488,474	**1.37**
Solar PV Systems	55,445	55,250	**0.35**	189,143	190,962	**0.96**
Total	3,581,933	3,585,052	**0.09**	3,699,248	3,806,857	**2.91**

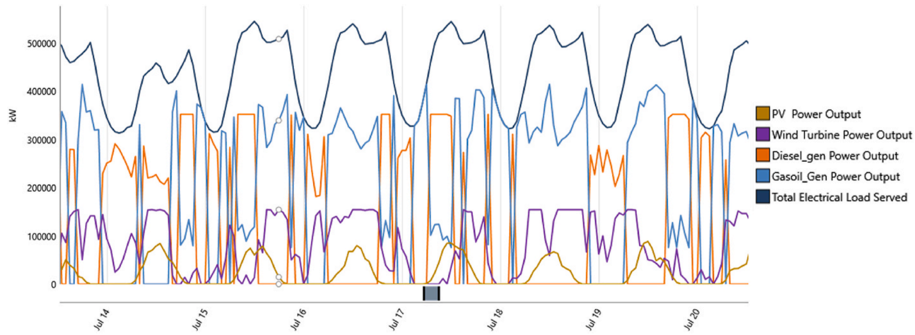

Fig. 5. Tenerife BaU power output profile for the generators and RES over a week period in July (HOMER Output).

Table 4
CO_2 emissions between the reported values and HOMER output.

	Actual Values (CO_2 ton)	Simulation Results (CO_2 ton)	Error (%)
Tenerife	2,065,132	1,936,850	6.21
Gran Canaria	2,119,442	2,230,336	5.23

obtained results from HOMER are compared with the numbers provided by the Canary Islands regional Government (Gobierno de Canarias, 2020) and are presented in Table 3.

The results show that the simulated model produces similar results compared with the official data(Gobierno de Canarias, 2020) with an overall margin of error that is less than 5%. The highest error can be noticed in Gran Canaria, where the electricity generated by the diesel generator is 6% higher than the actual value. This might be due to the limited information available for the power-efficiency curve of the generators used. Therefore, iterative tuning was performed for error minimization. Fig. 5 shows the contribution of each power component to meet the demand of Tenerife over a week. For the CO_2 emissions, the generators emission properties were iteratively tuned to match the reported values. The islands' error values are 6.21% for Tenerife and 5.23% for Gran Canaria as shown in Table 4. The COE in the BaU case is 0.157 €/kWh for Tenerife and 0.146 €/kWh for Gran Canaria.

In scenario 2 (S2), the optimization aims to find the generation mix that produces the least COE over the simulation duration, with different CO_2 emission penalties (0 €/ton, 30 €/ton and 60 €/ton) and new battery storage introduced to the model alongside the new RES, which are optimized to achieve the optimal COE based on the initial assumptions. Therefore, the CAPEX of the newly introduced components is included in this scenario. Fig. 6 and Fig. 7 visually summarise the RES fraction and COE under different CO_2 emission penalties for Tenerife and Gran Canaria, respectively. The optimization tool introduced new RES and storage to the BaU case for each island independently. For Tenerife, the optimal COE was found to be 0.121 €/kWh at 62.9% RES fraction as shown in Fig. 6, a 23% reduction in COE compared to the BaU case. Furthermore, the CO_2 emission intensity is reduced by 58.6% at the optimal COE compared to BaU. The optimal COE for Gran Canaria is obtained as 0.109 €/kWh at 70.4%, translating into a decrease in COE of 25% compared to BaU. This is also reflected in the CO_2 emission intensity, with a reduction of 66.4% compared to the BaU scenario as shown in Fig. 7. A similar result for Gran Canaria was obtained in (Cabrera et al., 2018), where the RES share was reported to be 75.9% based on the 2014 power system in the island.

As illustrated in Figs. 6 and 7, increasing the RES fraction beyond the optimal points initially comes at a slightly increasing COE For instance, increasing the RES penetration to 90% in both islands (without CO_2 emissions penalty) requires an additional 9.8% and 8.0% COE in Tenerife and Gran Canaria, respectively. Increasing the RES fraction further results into an exponential increase in system size requirements for both islands. Around 98% RES fraction in both figures, the cost of electricity generation is equal to that of the BaU, with significantly reduced CO_2 emission intensity. This point can be considered as a trade-off between COE and CO_2 emissions. However, the required CAPEX to increase the installation of RES to this point is very significant. For instance, the required CAPEX in Tenerife to reach 98% RES fraction is 5.2 billion € compared to 1.4 billion € at the optimal COE, this is an increase by 271% in CAPEX. Other factors that need to be considered if the 98% RES penetration is selected are the physical area and the technical limitations of the very large-sized battery. Beyond this point, the COE started to increase further than the COE of BaU, and the additional RES installations required to achieve this fraction approach astronomical values due to the optimization constraints dictating a 100% supply reliability requirement of the load profiles.

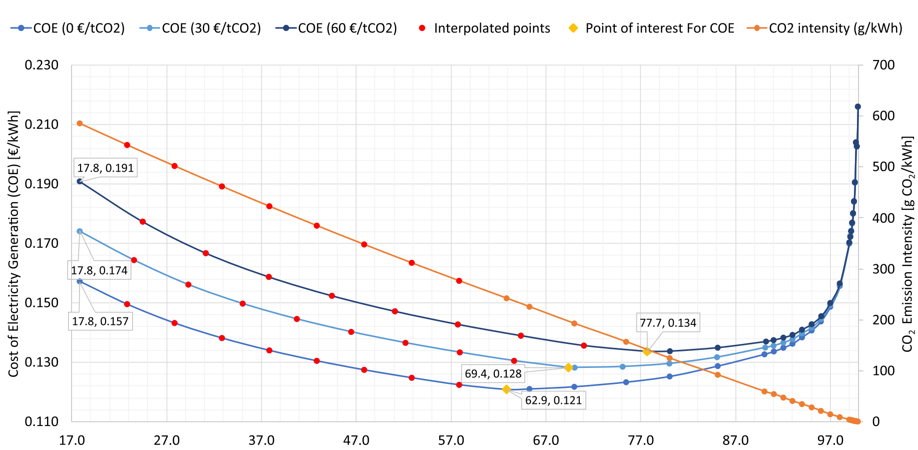

Fig. 6. COE and CO_2 emissions for different RES penetration and different CO_2 penalty for Tenerife.

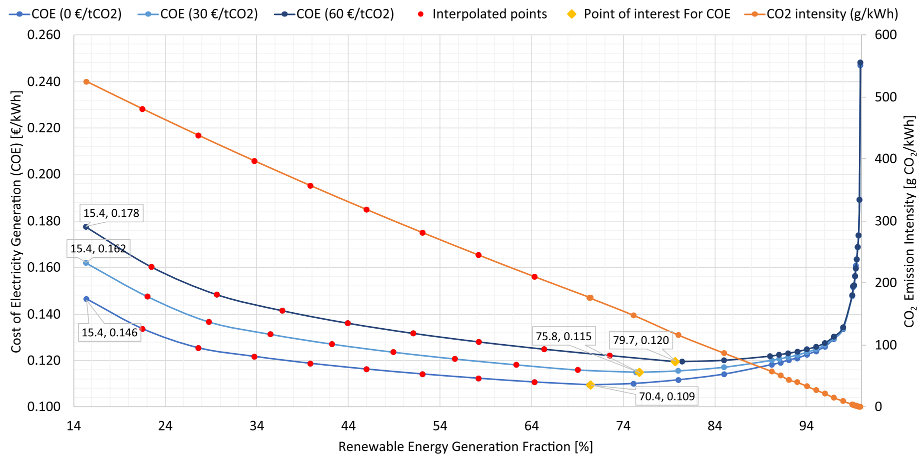

Fig. 7. COE and CO_2 emissions for different RES penetration and different CO_2 penalty for Gran Canaria.

By introducing penalties on CO_2 emissions, the curves shift vertically up for both islands. The COE for the BaU cases increases to 0.174 €/kWh and 0.191 €/kWh against CO_2 penalties of 30 €/ton and 60 €/ton in Tenerife (Fig. 6). The RES fraction increases in Tenerife by 10% and 23.5% for CO_2 penalties of 30 €/ton and 60 €/ton by comparing it with BaU case. In Gran Canaria, the optimal COE increases by a factor of 10% and 14% and the RES penetration increases by 5.8% and 10.7% for penalties of 30 €/ton and 60 €/ton, respectively. The CO_2 curves in Figs. 6 and 7 show a linearly decreasing behaviour, penalties further reduce the CO_2 emissions compared to the produced emissions at the optimal point without CO_2 penalties, the reduction is 20.4% and 35.3% in Tenerife and 16.1% and 34.1% in Gran Canaria for CO_2 penalties of 30 €/ton and 60 €/ton. Penalties shift the optimal COE and RES fraction points as installing more RES becomes the preferred economical choice against the increased penalties. Though, the penalties impact is inversely proportional to the initial RES fraction optimization since the CO_2 emissions are already reduced at the optimal point, leading to a decreased gap between the three sensitivity curves at higher RES penetrations. Similar trends are also observed for Gran Canaria as illustrated in Fig. 7.

4.2. Interconnected scenarios (S3, S4)

Both models of the BaU islands (S1) were combined with an interconnection whose details are described in Section 3, the new model is S3. The new COE with the interconnection using the BaU installed capacities in each island is found to be 0.138 €/kWh. To compare the results of this scenario with the aggregation of S1 and S2, their weighted average is calculated using the following equation.

$$W = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{8}$$

where w_i weights applied to values, X_i data values to be averaged and n number of terms to be averaged.

Comparing the results with the reported from S1, the interconnection (S3) provided a lower COE by ~9% compared to the weighted average COE in BaU case (S1) for both islands, which is found to be 0.152 €/kWh from Equation (8). The interconnection increases the utilization of existing RES assets compared to the average RES penetration for both islands in S1, the new RES utilization factor for S3 is 19.1% which is higher by 14.5% comparing it with the average BaU in S1. This is because the system in S3 utilises the interconnection to transfer more energy from the thermal generator that had lower fuel prices. Furthermore, the interconnection maximizes the use of the available RES. This is reflected in the produced emissions, which are reduced by 9.1%.

Additional RES and battery storage are integrated into the model introduced in S3 to create S4 model. The RES fraction of the system is first varied to obtain the optimal combined system COE with interconnection. Fig. 8 presents the COE against RES fraction for the

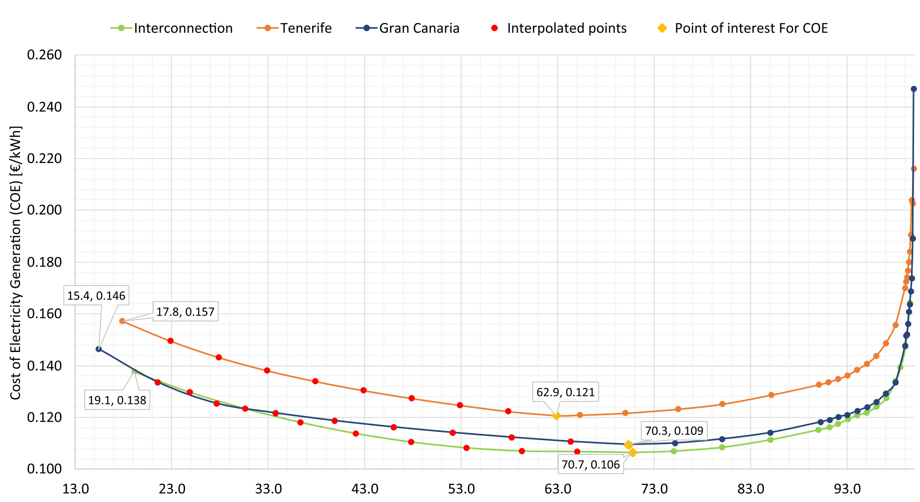

Fig. 8. The COE under different RES fractions for S4 and comparing it with results in S2.

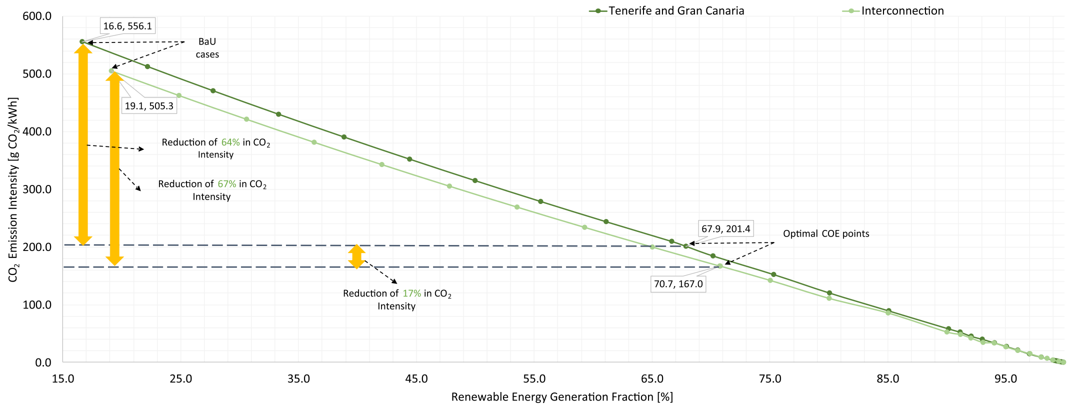

Fig. 9. Comparison between CO_2 emissions generated from S4 and combined S2.

interconnection case without CO_2 penalties and a comparison with the results obtained in S2, the comparison covers the cases where no CO_2 penalties are applied. S4 provides a lower optimal COE and a higher RES penetration than the values obtained in S2 for each island individually. Also, this observation is true when compared with the results in S3. The difference between optimal COE in Gran Canaria (S2) and the results reported from S4 are not significantly different; the difference is only 2.8%. On the other hand, COE in Tenerife was reduced by 12.4% with the interconnection. The COE for the interconnection was lower compared to Tenerife until the RES fraction reached 98%. After this point, the COE of S2 and S4 becomes very high. For Gran Canaria, the COE until 97% RES fraction is slightly higher than the interconnection's COE. The weighted average of the optimal COE for Tenerife and Gran Canaria independently is 0.115 €/kWh which is still higher than the interconnection's optimal COE by 8.5%.

From an environmental perspective, the interconnection reduces the CO_2 emissions compared to the combined CO_2 emissions of the Tenerife and Gran Canaria Islands for the BaU case as shown in Fig. 9. The reduction (around 9%) is due to the increased RES penetration in BaU case for the interconnection (Scenario 1 vs. Scenario 3). Also, the optimization tool increases the amount of electricity generated from thermal generators that were more efficient. Thus, reducing the amount of fuel needed to generate the same amount of energy using less efficient generators leads to reduced CO_2 emissions.

The reduction in CO_2 emissions at the optimal RES penetration for the interconnection case compared to S3 is estimated at 67% and 64% when comparing the combined islands emissions between S1 and S2. The CO_2 emission intensities with interconnection for both BaU (S3) and optimized scenarios (S4) are lower than in non-interconnected cases (S1 and S2). Another observation is that the reduction in CO_2 intensity at optimal COE for interconnection and average COE for non-interconnected cases is 17% as highlighted in Fig. 9. At a higher RES fraction (95% >) the CO_2 emissions are similar for combined S2 and S4 because their fuel generators utilization becomes significantly limited.

4.3. Interconnection RES fraction and NPC

One significant advantage of the interconnection is that it reduces the total RES capacity required to produce the optimal results, this is due to the reduced amount of excess energy in the system. The excess energy in the interconnection is reduced by 74.6% compared with combined excess energy for non-interconnected islands. In other words, the interconnection is able to utilize the surplus power produced in one island to serve the load demand in the other and charge the storage batteries, which leads to lowering the overall RES capacity requirement. This leads to a lower new CAPEX and OPEX. The load curve variation can also influence the interconnection utilization in each island such that the addition of both loads can potentially lead to a flatter aggregated curve, leading to better resources utilization. On the other hand, the non-interconnected islands modelled in S2 need a more extensive battery storage system to reduce the amount of excess energy, but this requires a massive storage system which is directly reflected on the COE. The RES capacity difference between the interconnection scenario (S4) and the combined islands scenario (S2) is shown in Fig. 10. The total RES

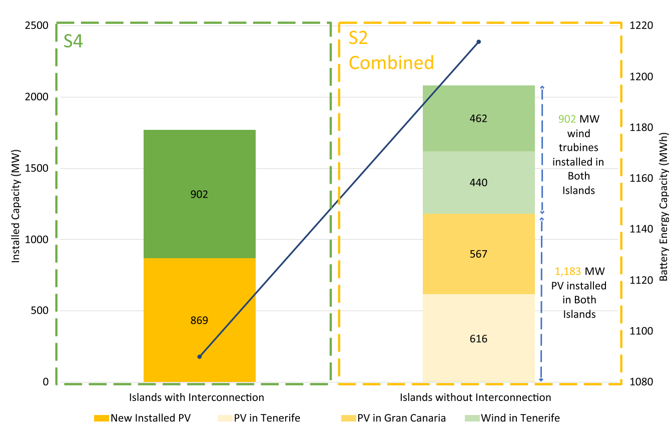

Fig. 10. Additional installed RES capacity in the S2 and S4.

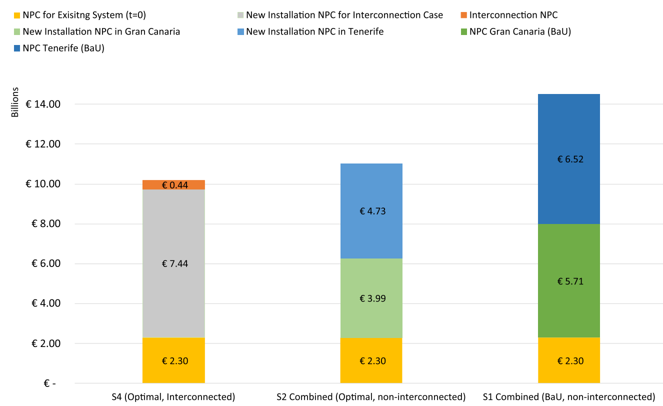

Fig. 11. NPC of the various scenarios (project lifetime assumption: 25 years).

capacity in the interconnection scenarios is 1771 MW while the sum of the RES capacity in the two islands independently is 2085 MW. This is a significant difference of 314 MW (15.1%). The difference is mainly in the installed wind turbine capacity, the wind turbine had higher CAPEX and OPEX as demonstrated in Table 2. Similarly, there is a difference of 123.7 MWh (10.2%) in the installed storage capacity with 1090 MWh installed in the interconnection scenario and 1213.7 MWh installed independently in the two islands.

The results obtained here are compared with the projected RES installations in Tenerife and Gran Canaria by 2050 as reported in (Gils and Simon, 2017; Hernandez et al., 2017). The studies provided capacities for new RES installations to achieve 100% renewables operation, while proposing an interconnection between the seven islands in 2050. For Tenerife and Gran Canaria in particular, the projected RES installations are 5081 MW for the PV systems and 1480 MW for the wind turbines, totalling 6561 MW. On the other hand, the orders of magnitude of the results presented in the present paper illustrate a lower overall required capacity for the optimal 70.7% RES fraction point with interconnection at 1771 MW. In contrast, this number approaches 4500 MW at a 99% RES fraction, though at a higher COE.

The reduction in the RES and storage capacities with the interconnection leads to a lower NPC. This is demonstrated in Fig. 11. It is seen that even after taking the base cost of interconnection into account from Equation (7), the NPC of the interconnected scenario (S4) is less than the sum of the NPC of the two islands independently (S2). The difference between the NPC of the two scenarios is 0.84 billion € which is a reduction of 7.6% (for the project lifetime assumption of 25 years). The interconnection cost in S4 represents only 4.3% of the scenario's NPC. Hence, the lower NPC translates to a lower COE. Furthermore, the interconnection reduces the total NPC required by 29.9% compared to combined NPC for BaU because of the reduced consumption of fuel which is also reflected in the maintenance and operation cost of the thermal generation units.

4.4. *Impact of varying interconnection CAPEX on estimated COE*

In this study, the cost of interconnection has been calculated based on an empirical formula developed by the authors, as presented in Equation (7). The formula estimates the cost of a given interconnection based on its power rating and length, aiming to approximate the investment order of magnitudes. A literature case study in (Gils and Simon, 2017) proposes two interconnectors between Tenerife and Gran Canaria with a combined 384 MW capacity. The authors estimate the interconnection cost at 430 million €. Plugging similar capacity for a single interconnector in Equation (5) results in 374 million € (1€ = 1.179 $), with a 12.8% error between both estimates.

Overall, the variability of CAPEX in HVDC projects is influenced by the particularities of each project such as the capacity, location, used technology and regulations (Alassi et al., 2019). To provide a more inclusive interconnection economic analysis, the optimal COE for the interconnected system with the capacities obtained in S4 is calculated for a range of interconnection CAPEX while fixing the capacity to 500 MW as demonstrated in Fig. 12. The figure highlights the optimal COE value for S4 and S2 for both islands and the different COE values with different initial costs. It is noticed that the breaking point occurs when the interconnection CAPEX exceeds 1225 million €. After this point, the combined optimal average COE for both islands becomes lower than the optimal COE with interconnection (from a typical system owner perspective) as shown by the orange shaded area boundary in Fig. 12. From an individual island perspective, an interconnection CAPEX beyond 1695 million € is required before the breakeven point with Tenerife COE. These results serve to demonstrate the economic viability of the optimized interconnection scenario even with the described uncertainty, meaning that the estimated interconnection cost has to triple before losing the economic justification. This is in addition to the previously demonstrated environmental benefits of interconnection.

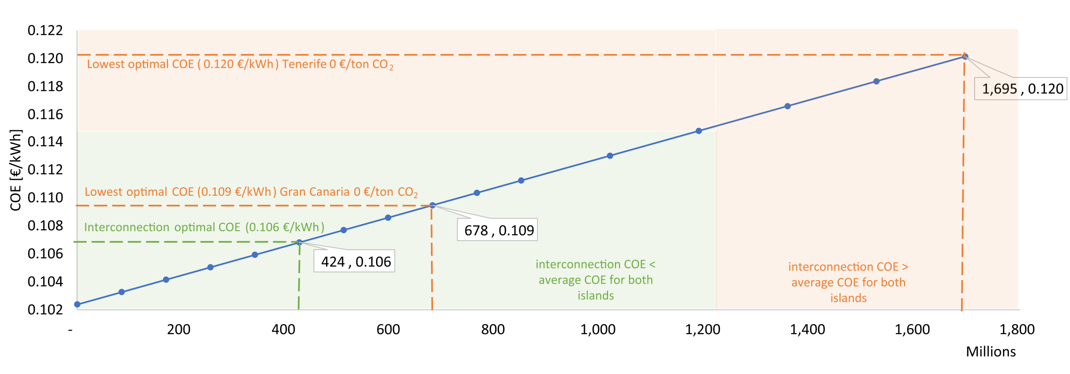

Fig. 12. The COE for interconnection by varying the interconnection initial cost.

Table 5
Sensitivity analysis for optimal COE in S4 under different cost of interconnection and reduced pre 2019 installed system CAPEX.

		Pre 2019 Installed System (S1) CAPEX [Millions €]				
		–	**1150**	**1150**	**1725**	**2300**
Cost of Interconnection [Millions €]	**-**	0.078	0.084	0.090	0.096	0.102
	84.75	0.079	0.085	0.091	0.097	0.103
	423.75	0.082	0.088	0.094	0.100	***0.106***
	762.75	0.086	0.092	0.098	0.104	0.110
	1695.00	0.096	0.102	0.108	0.114	0.121

4.5. Impact of interconnection cost and CAPEX on COE

Alongside the interconnection cost, the estimated BaU (S1) CAPEX is determined by using the approach discussed in section 3.3.2. The values obtained from Equation (6) are added to all consequent scenarios in this paper as the S1 system is assumed to remain active in all of them. To ensure the visibility of the proposed solution, 2D sensitivity analysis for the S1 CAPEX and the interconnection cost is carried out on the optimal COE for S4 as shown in Table 5. This analysis evaluates the impact on the optimal COE for S4, resulting from reducing the estimated S1 BaU CAPEX from the ceiling obtained from Equation (7) down to zero (as considered by some literature sources), in addition to simultaneously varying the interconnection cost around the value obtained from Equation (5).

The cell corresponding to 423.75 M€ interconnection cost and 2300 M€ S1 CAPEX represents the optimal base case with interconnection, both values are then varied to observe the impact on COE. For instance, the COE ranges between 0.082 €/kWh and 0.106 €/kWh at 423.75 M€ interconnection cost and different S1 CAPEX values, thus reducing the COE for underestimated S1 CAPEX cases by up to 22.6% of the base case. This reduction is significant and shows the impact of neglecting this parameter on the estimate accuracy and relevance. On the other hand, the COE value obtained at both zero S1 CAPEX and zero interconnection cost can be used by system designers or policymakers as a lower-end benchmark for system evaluation under different S1 CAPEX and interconnection annualized cost assumptions beyond those presented in the table, which should be added to the COE calculation formula numerator in Equation (1).

5. Conclusion and policy implications

This study delivers insightful techno-economic analysis on different RES and storage penetration scenarios at the Canary archipelago's most populated two islands, Tenerife and Gran Canaria. The covered four scenarios in this paper investigate different generation mix options with cost minimization, RES output maximization and emission reduction targets. The possibility of interconnection between both islands is also investigated.

The optimal COE for Tenerife is 0.121 €/kWh at 62.9% RES fraction without CO_2 penalties, this translates into a reduction of 23% in COE from 2019 numbers. The CO_2 intensity declines by 59% at the optimal COE compared to BaU. Furthermore, the COE reaches 0.134 €/kWh at 77.7% RES fraction with 60 €/ton for CO_2 emissions. For Gran Canaria, the optimal COE is less than COE at BaU by 25.3%, this is achieved when the RES fraction is 70.4% without CO_2 penalties and it reached 0.120 €/kWh at 79.7% RES fraction with 60 €/ton for CO_2 emissions. The introduced CO_2 penalties slightly increase the COE compared to the savings that are achieved in terms of cost and CO_2 emissions when RES penetration is increased. On the other hand, the CO_2 penalties do not substantially increase the optimal RES penetration points in the Islands.

The electrical interconnection between Tenerife and Gran Canaria improves the utilization of resources in both islands, effectively reducing the overall required new RES and storage capacity, NPC and COE. The optimal COE for interconnection offered a lower COE by 30.3% in comparison to BaU case (S1) and by 8.5% compared to the weighted average optimal COE for the islands (S2). Furthermore, the interconnection optimization (S4) reduces the CO_2 emission intensity by ~70% compared to CO_2 produced in both islands (S1 combined) and by 17% in comparison with optimize S2. The optimization results suggest that a 500 MW interconnection between Gran Canaria and Tenerife can reduce their combined electricity generation system's NPC by 0.84 billion € (7.6%) over the next 25 years compared to the optimal case in S2 with no interconnection. In addition, the paper further investigates the effect of interconnection's initial cost on the optimal COE. The results show that the cost of the interconnection can be increased up to 1225 million € before the COE becomes higher than the optimal combined average COE of the isolated, individually operated islands. Another sensitivity analysis is performed to evaluate the impact of interconnection cost and S1 system CAPEX on the COE, which is often not considered in the literature. This work has also proposed a new approach to investigate an electrical interconnection between two independent power systems using HOMER software for techno-economic analysis. The approach enables the inclusion of the interconnection capacity and losses into the optimization.

Collectively, the paper demonstrates that more RES installations in isolated systems can minimize the overall costs, through a comprehensive case study from the Canary Islands. The external dependency on imported fossil fuel in this case study is reduced significantly to less than 30% compared to the traditional fuel power stations that generate more than 80% electricity today. Such transition could be reflected in different aspects of the islands' society such as more employment opportunities in the power and sustainability sector. Higher long-term investment opportunities can also be expected as a result of the overall reduced COE generation. Also, reducing CO_2 through higher RES penetration helps maintain more sustainable life on the islands. Different types of RES can be introduced to the system to cover the growth in demand, hydrogen can be used in the future to equilibrate the demand and supply in different seasons of the year by saving the excess energy generated by RES which can be later used to generate power. However, the current development in hydrogen makes it less attractive as it requires large tanks to store because it is challenging to liquefy and the producing technologies are still in the development phase. Biomass can also help reduce emissions by converting residues and municipal solid waste into fuel that can be used to generate electricity and reduce the amount of waste produced instead of creating dumps and incinerating plants.

Energy planners and decision-makers can use this study to plan the future of the Canary Islands energy sector or other similar territories in the EU and around the world, by establishing policies and initiatives to further encourage using innovative solutions to create more sustainable energy systems in islands while offering a reduce COE and lower CO_2 emissions as the findings of this paper showed. The paper is aligned with the different initiatives proposed by the EU and Spanish government for energy sustainability by offering a reliable energy system for the most populated two islands in the Canary archipelago. Thus, the results obtained can help to enhance the current policies further.

CRediT authorship contribution statement

Yazan Qiblawey: Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Abdulrahman Alassi:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration. **Mohammed Zain ul Abideen:** Investigation, Writing – original draft, Writing – review & editing. **Santiago Bañales:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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