Energy Policy 188 (2024) 114056

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Technical-economic limitations of floating offshore wind energy generation in small isolated island power systems without energy storage: Case study in the Canary Islands

Moisés Martín-Betancor [a], Javier Osorio [b,*], Alejandro Ruíz-García [c], Ignacio Nuez [c]

[a] Department of Cartography and Graphic Expression in Engineering, Universidad de Las Palmas de Gran Canaria, Campus Universitario de Tafira, Las Palmas de Gran Canaria, 35017, Spain

[b] Department of Business Administration and Management, Universidad de Las Palmas de Gran Canaria, Campus Universitario de Tafira, Las Palmas de Gran Canaria, 35017, Spain

[c] Department of Electronic Engineering and Automation, Universidad de Las Palmas de Gran Canaria, Campus Universitario de Tafira, Las Palmas de Gran Canaria, 35017, Spain

ARTICLE INFO

Keywords:
Offshore wind energy
Isolated electrical systems
Small electricity systems
Energy curtailment
LCOE

ABSTRACT

Coastal areas committed to the development of affordable and clean energy sources can find significant means to achieve their decarbonization objectives in offshore wind technology for power generation. However, the development of this technology in island territories with small-scale isolated electrical systems faces technical constraints that, in turn, translate into economic limitations. The objective of this study is to determine offshore wind energy curtailment and its impact on the LCOE in island territories with small-scale isolated electrical systems. To accomplish this, the data of electrical energy demand and generation of onshore renewable energy and conventional energy over a year have been used, with the Canary Islands (Spain-EU) adopted as a case study. The regional government there has established total decarbonization of its economy by 2040 as the central axis of its energy policy. The results show percentages of offshore wind energy curtailment exceeding 35% and an increase in the LCOE of up to 17%. One of the conclusions highlights the need for governmental action to neutralize this increase in the LCOE. This study sheds light on the technical and economic implications for government energy plans promoting the large-scale deployment of floating offshore wind facilities in island territories.

1. Introduction

In the 2015 Paris Agreement, the signatory parties agreed to achieve a net reduction of Greenhouse Gas emissions (GHG) to limit annual global warming (Feng et al., 2022; United Nations, 2015). The European Union (EU) presented the package called "Fit for 55″ to achieve climate neutrality by 2050 and achieve a net reduction of GHG by at least 55% compared to 1990 emissions by 2030 (The European Parliament and the Council of the European Union, 2023). In July 2021, the Commission presented Europe's new 2030 climate targets; it seeks to increase the target to at least 40% renewable energy sources in the EU's overall energy mix by 2030. In May 18, 2022, the Commission published the REPowerEU plan, which sets out a series of measures to accelerate the clean energy transition. The above are examples of energy policies aimed at climate neutrality, reflecting the importance of decarbonizing economies through the use of renewable energy sources. A significant portion of GHG emissions are produced in the generation of electrical power from fossil fuels (European Court of Auditors, 2017). An alternative for coastal territories is the generation of offshore wind energy. Offshore wind energy increased its cumulative deployed capacity between 2010 and 2021, from 3.1 GW to 55.7 GW (IRENA, 2022). According to forecasts from the International Renewable Energy Agency (IRENA, 2019), to meet the objectives of the Paris Agreement, the installed power of offshore wind electricity worldwide will need to be 228 GW by 2030 and 1000 GW by 2050. According to the International Energy Agency (IEA, 2019), offshore wind energy will account for half of Europe's electricity generation in 2050. The significant cost reduction experienced by offshore electricity generation technologies makes exploiting the great potential offered by offshore wind energy an excellent opportunity (Musial et al., 2022).

Economic profitability is a key variable in the decision to invest in offshore wind power generation farms. The most commonly used measure to evaluate the economic profitability of an investment in power

* Corresponding author.
E-mail address: javier.osorio@ulpgc.es (J. Osorio).

https://doi.org/10.1016/j.enpol.2024.114056
Received 1 September 2023; Received in revised form 5 February 2024; Accepted 25 February 2024

Abbreviations

GHG	Greenhouse Gas
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
NREL	National Renewable Energy Laboratory
ES-GC	Electrical System of the island of Gran Canaria
ES-LZFV	Electrical System of the islands of Lanzarote y Fuerteventura
EU	European Union
VRE	Variable Renewable Energy

generation facilities is the Levelized Cost of Energy (LCOE) (Pires et al., 2022). The LCOE is calculated as the ratio between the sum of all costs incurred during the lifetime of an electricity generating plant and the sum of the actual amounts of energy generated (Martinez and Iglesias, 2022). This index is usually expressed in annual terms and is used to compare profitability between different technologies for power generation (Tran and Smith, 2018). At the most basic level, the calculation of the LCOE obeys the expression shown in Eq. (1) (Aldersey-Williams and Rubert, 2019).

$$LCOE = \frac{Annual\ Fixed\ Cost + Annual\ Variable\ Cost}{Annual\ Energy\ Generation} \left(\frac{€}{\mathrm{MWh}}\right) \quad (1)$$

The expression shown in Eq. (1) corresponds to the one commonly used when calculating the LCOE for annual periods. Other expressions for the LCOE include the influence of monetary inflation over time (Loth et al., 2022). This is the case when the aim is to evaluate the investment over the entire life cycle of a project, which, being relatively long, is subject to inflationary monetary dynamics (Johnston et al., 2020). The adoption of the LCOE has become widespread as an indicator for decision-making in investments for power generation (Aldersey-Williams and Rubert, 2019; Shen et al., 2020).

In the case of floating offshore wind farms, there is not enough data on the values achieved by this variable. Globally, the development trajectory of a floating offshore wind energy market continues at the pilot scale, totaling 123 MW floating offshore wind energy projects operating globally at the end of 2021 (Musial et al., 2022). Studies have been published that contribute to the evaluation of the LCOE in floating offshore facilities. Shen et al. (2020) conducted a comparison of the LCOE among different electricity floating generation technologies highlighting that there is a lack of a standard methodology for calculating the LCOE for variable renewable energy (VRE), which results in a high range of LCOE for each technology. Lerch et al. (2018) conducted a sensitivity study with 325 input parameters to identify which variables are most influential in calculating the LCOE for floating offshore wind farms, identifying the key parameters that have a significant influence on the LCOE; these are linked with manufacturing costs: wind turbine cost, substructure, and mooring system. Aldersey-Williams and Rubert (2019) obtained LCOE values for floating offshore generation in the range between 50 and 68 €/MWh, for an installation of 844 MW and a capacity factor of 48%. In a study on floating offshore installations, Maienza et al. (2020) evaluated different options and components in investment and maintenance analyzing Semi-Submersible Platform, the Spar Buoy and the Tension Leg Platform for 125 MW farms, at a distance of 165 km from the port, and 16 km from the coast, with depths between 130 and 140 m, obtaining average LCOE values of 97.4 €/MWh. However, in the study by Clauser and Ewert (2018) for a 5 MW offshore wind farm, values of the LCOE for offshore wind electricity generation of between 123.4 and 172 €/MWh were obtained. The disparity of values is due to the fact that this is a novel technology, with little accumulated experience, and with high complexity of floating installations; therefore, detailed sensitivity and optimization studies must be carried out in each specific project to assess the feasibility of this type of projects (Barter et al., 2020; Chen and Hu, 2022).

There are several factors that are not reflected in traditional LCOE calculations (Aldersey-Williams and Rubert, 2019; Sklar-Chik et al., 2018), such as the variability of renewable energies since conventional backup electricity and/or storage is typically needed. This is an additional cost that is not accounted for in the LCOE of renewable energy. Furthermore, in markets with dynamic pricing models, the LCOE does not take into account price variation throughout the year. The environmental benefits of using renewable energies are also not valued in the LCOE (Vargas-Salgado et al., 2022). Fuel supply risks and the volatility of fossil fuel prices are also not present in the LCOE, nor are regulatory risks (Partridge, 2018). Additionally, interest rates reflect the weighted cost of capital of an investment; setting a higher fixed interest rate for an LCOE calculation can favor low capital investment projects over high capital investment projects, such as the installation of floating offshore wind farms (Branker et al., 2011). Reichenberg et al. (2018), in their study on penetration levels of wind and solar energy, conclude that LCOE values increase considerably when the penetration of renewable energy in an electrical system is over 80%; this increase in LCOE is due to the incorporation of energy storage systems and the exponential growth of energy curtailment from this value onwards.

From the energy demand perspective, in isolated electrical systems there can be situations of excess in energy supply when new VRE is incorporated. The security of electricity supply is one of the major problems that arise when the penetration of VRE in isolated electrical systems increases (Mohandes et al., 2019). In the literature, there are numerous studies on the response of electricity generation systems to abrupt variations caused by high contributions of VRE and their impact on grid stability. Pandey et al. (2013) conducted a state-of-the-art review of power system types and their different control strategies for the stability of load-frequency based electrical systems. Wind energy fluctuations are a major problem for managing electricity grids and microgrids, which can cause instabilities in grid frequency and voltage oscillations that require control (Ahn and Hur, 2022; Heetun et al., 2016). Johnson et al. (2020) studied the stability of the electrical grid with high penetration of renewables; the fast frequency response of the inverters that form the network, along with other technological changes, could help mitigate the system's low levels of inertia. The results showed that the displacement of conventional generation by renewable generators creates critical inertia situations and, as a result, of stability. Some authors have integrated frequency stability in their studies of electrical networks, concluding that a certain amount of synchronous generation is required for stability (Chang et al., 2016; Denholm and Hand, 2011). Tamrakar et al. (2017) studied the stability of the isolated electrical system in the Penghu Islands, subject to high penetration of renewable energies. To increase the penetration of renewable energies, they propose expanding the rapid response capacity through diesel engines, thereby improving the reliability and energy quality of the electrical system and letting smaller battery units as energy storage systems. The high penetration of renewable energy sources leads to changes in regulations, norms, and requirements that, being technically and economically necessary, need to be globally harmonized (Al-Shetwi et al., 2020).

Public institutions responsible for energy matters in isolated island territories with small-scale electrical systems are therefore facing a complex situation. On one hand, they must consider fulfilling the decarbonization objectives recommended or committed to in international agreements. On the other hand, they must promote the development of clean and affordable energy without compromising public funds that would result in a loss of services received by citizens (e.g. education, healthcare, neighborhood services); that is, public institutions must ensure that investments in renewable technologies are economically profitable or represent a minimal additional burden for the public treasury. Moreover, they must guarantee the security of electricity supply to businesses and individuals, in such a way that the incorporation of renewable electricity into the network does not affect the system's stability. Therefore, the energy policies of these territories must balance the mutual influence between these dimensions.

The purpose of this study is to analyze the technical and economic implications of planning offshore floating wind power in small isolated island electrical systems. This study is structured as follows: first, it justifies the adoption of the Canary archipelago (Spain-EU) as a case for analysis; next, it describes the analysis method adopted, which can be applied to the study of other island territories with small isolated electrical systems. The results and discussion section reflects the application of the proposed method and its technical and economic implications for the study territory. Finally, in the conclusion section, aspects that may be relevant in defining the energy policy of island territories with small isolated electrical systems are presented.

2. Materials and methods

2.1. Description of the case study

The proposed methodology will be applied to the real case of a European archipelago, the Canary Islands (Spain-EU). This territory has been chosen because it is made up of several small isolated electrical systems. The Canary Islands are located in the Atlantic Ocean, off the northwestern coast of Africa, between 22° and 35° north latitude. There are seven main islands with a permanent population of 2,172,944 inhabitants and an equivalent tourist population close to 300,000 inhabitants (Institute of Statistics of Canary Islands, 2023a,b). In terms of electrical interconnection, the islands are isolated from each other (except in the case of the islands of Lanzarote and Fuerteventura, which are interconnected by a 50 MW capacity submarine cable).

The Canary Islands have been the subject of several studies to analyze their potential for the installation of offshore wind farms (Abramic et al., 2021; Díaz and Soares, 2021; Schallenberg-Rodríguez and García Montesdeoca, 2018). The study by Díaz and Soares (2021) adopted a set of criteria to minimize environmental impacts and reduce conflicts between stakeholders in marine uses. Similarly, it reduced the potential for socio-economic controversies, derived mainly from the impact on tourism activities, by establishing minimum distances from the coast of more than 8 km for offshore wind facilities. It also ensured that there is no conflict between current and potential marine uses by establishing separation buffers of at least 1 km between the different uses assigned to marine areas. For the above reasons, the work of Díaz and Soares (2021) was adopted in our study as a reference for the location of optimal offshore wind farm sites. The study by Díaz and Soares (2021) identified two optimal maritime areas for the location of offshore wind farms that would only inject energy into the electrical system of the island of Gran Canaria (ES-GC), and into the electrical system of the islands of Fuerteventura and Lanzarote (ES-LZFV). The identified surfaces imply the need to incorporate floating offshore wind technology due to their great depths. In this work, these electrical systems are taken as reference, and the sizing of offshore wind installations is studied, taking into account the size of the electrical system into which they are going to inject energy. The sustainable energy strategy in the Canary Islands, developed by the regional government, has set a goal that by 2030 offshore wind power will be 200 MW in the ES-GC electrical system and 100 MW in the ES-LZFV electrical system. The goals are more ambitious for the year 2040, with offshore wind power exceeding 800 MW in each system to contribute to the total decarbonization of the Canary Islands' economy (Government of the Canary Islands, 2022a). These values are intended to electrify sectors of activity heavily dependent on fossil fuels, such as land transport or the desalination of seawater for domestic use, as well as the generation of green hydrogen for use, among others, in maritime transport.

The electrical power capacity of the islands amounted to 3403 MW in 2021 (Government of the Canary Islands, 2023). 73.8% of the electricity generation is produced by power plants that use fossil fuel (Government of the Canary Islands, 2023). Being an archipelago, it can benefit from the installation of offshore wind farms to increase the generation of electricity from renewable sources. This potential is enhanced by the fact that high seasonal wind regimes occur in some areas of the surrounding offshore surface.

The installed conventional and renewable electrical power between the years 2019 and 2021 in the two considered electrical systems are shown in Table 1. As can be seen, between the years 2019–2021 there has been no variation in conventional electrical power. On the contrary, onshore renewable electrical power has experienced an increase in that period of 27.2% in the ES-GC electrical system, and 53.8% in the ES-LZFV electrical system.

In Table 2, the demand for electrical energy, the generation of conventional electrical energy, and the generation of renewable electrical energy are shown monthly for the years 2019–2021 of the ES-GC electrical system. It is observed that the monthly demand for electrical energy remains near 300 GWh and the contributions from renewable energies are higher in the summer months. The demand for electrical energy was affected in the years 2020 and 2021 due to the Covid-19 pandemic. On the other hand, the proportion of onshore renewable electricity generation has been increasing in the three years considered, growing from 16.4% in 2019 to 21.5% in 2021.

As shown in Table 2, onshore renewable energy generation is much higher in the summer months than in the winter months. This is due to the prevailing wind regime in each season. This high seasonality of wind energy generation in the studied electrical systems can be a limiting factor for the sizing of new offshore wind farms (Zheng et al., 2017). Fig. 1 shows the average and seasonal hourly profile of onshore renewable power generated in the ES-GC electrical system in 2021. Fig. 2 shows an estimate of the average hourly and seasonal wind speed at 100 m height in 2021 (Hersbach et al., 2023), for the offshore wind zone of the ES-GC electrical system (Díaz and Soares, 2021). As can be seen in Fig. 1, the average hourly generation of onshore renewable power was higher in the summer. Similarly, in Fig. 2 it is shown that the profile of the average offshore wind speed for offshore wind energy generation was higher in the summer. Therefore, there may be a higher percentage of offshore energy curtailment in the summer season. It is worth noting that this offshore wind speed profile is different from that of almost the entire region of 30°–60°N in the Northern Hemisphere, in which the highest speed regimes are reached in winter due to the influence from cold (Zheng et al., 2017). However, there is a broad coincidence with the wind power pattern in Central California Coast, which maximizes in spring and summer (Wang et al., 2019).

In order to determine the balance between supply and demand of power in the ES-GC electrical system, data from the ISIOS database of the electrical system operator (REE, n.d.) was used, which shows the profile of hourly and seasonal power demand in 2019. As shown in Fig. 3, the demand for electrical power is quite homogeneous in the different seasons throughout the year.

Fig. 2 shows that in the year 2021, in the offshore area of the ES-GC electrical system, although there were differences in the average wind speed for each season, the average hourly wind speed regime in each season remained with a certain stability. In the autumn, winter and spring seasons, the hourly average wind speed differences were mostly within the range of 1 m/s; while in summer, the maximum hourly difference in the average wind speed was within the range of 1.5 m/s. This homogeneity in seasonal wind speeds is a favorable factor to allow a stable operating regime of offshore wind turbines. It is worth noting that in winter, the season with the lowest wind speed, the average wind speed, estimated between 7 and 7.5 m/s, can be categorized as Wind Power Class 3–4, which implies a quality of site between good and very good. Under these conditions, the offshore wind farms can contribute to the energy mix of the ES-GC electrical system. These values contrast with those observed in almost the entire region of 30°–60°N in the Northern Hemisphere, with wind energy belonging to Class 7 (Zheng

Table 1
Installed electrical power in the ES-GC and ES-LZFV electrical systems (years 2019–2021). Source: Government of the Canary Islands (2023).

		ES-GC			ES-LZFV		
Technology		Electrical Power (MW)			Electrical Power (MW)		
		2019	2020	2021	2019	2020	2021
Conventional		999.18 (83.3%)	999.18 (81.0%)	999.18 (79.5%)	419.28 (85.4%)	419.28 (83.8%)	419.28 (79.2%)
Renewable	Onshore wind	159.30 (13.3%)	193.94 (15.7%)	205.24 (16.5%)	50.96 (10.4%)	60.16 (12.0%)	89.36 (16.8%)
	Photovoltaic	40.62 (3.4%)	40.70 (3.3%)	49.14 (4.0%)	20.77 (4.2%)	20.77 (4.2%)	20.94 (4.0%)
Total		1199.10	1233.82	1258.56	491.01	500.21	529.58

Table 2
Monthly evolution of the demand and generation of electricity in the ES-GC electrical system (years 2019–2021). Source: ISIOS database of the electrical system operator (REE, n.d.).

Month	2019			2020			2021		
	Electricity demand (GWh)	Electricity generation from conventional sources (GWh)	Electricity generation from renewable sources (GWh)	Electricity demand (GWh)	Electricity generation from conventional sources (GWh)	Electricity generation from renewable sources (GWh)	Electricity demand (GWh)	Electricity generation from conventional sources (GWh)	Electricity generation from renewable sources (GWh)
January	265.31	242.87	22.44	295.43	271.50	23.93	262.76	223.31	39.46
February	290.57	242.10	48.47	269.86	227.48	42.38	235.00	203.58	31.42
March	273.95	236.53	37.43	276.72	224.83	51.89	262.14	211.33	50.80
April	284.91	232.98	51.93	229.99	196.15	33.84	253.19	218.09	35.10
May	277.89	234.95	42.94	243.09	201.51	41.58	263.02	177.23	85.80
June	299.43	218.87	80.56	251.87	200.67	51.20	261.45	175.57	85.87
July	304.99	229.05	75.94	281.21	201.84	79.37	284.71	197.97	86.74
August	292.40	237.67	54.73	290.01	204.80	85.21	288.37	202.97	85.40
September	306.34	262.02	44.32	281.28	229.51	51.76	288.07	229.76	58.31
October	289.07	234.57	54.50	280.40	230.24	50.16	290.90	226.30	64.60
November	292.93	264.91	28.02	268.74	243.20	25.55	277.49	238.47	39.02
December	265.31	242.87	22.44	268.03	237.39	30.64	284.01	247.36	36.65
Total	3472	2903	568	3237	2669	568	3251	2552	699
Percentage		83.6%	16.4%		82.5%	17.5%		78.5%	21.5%

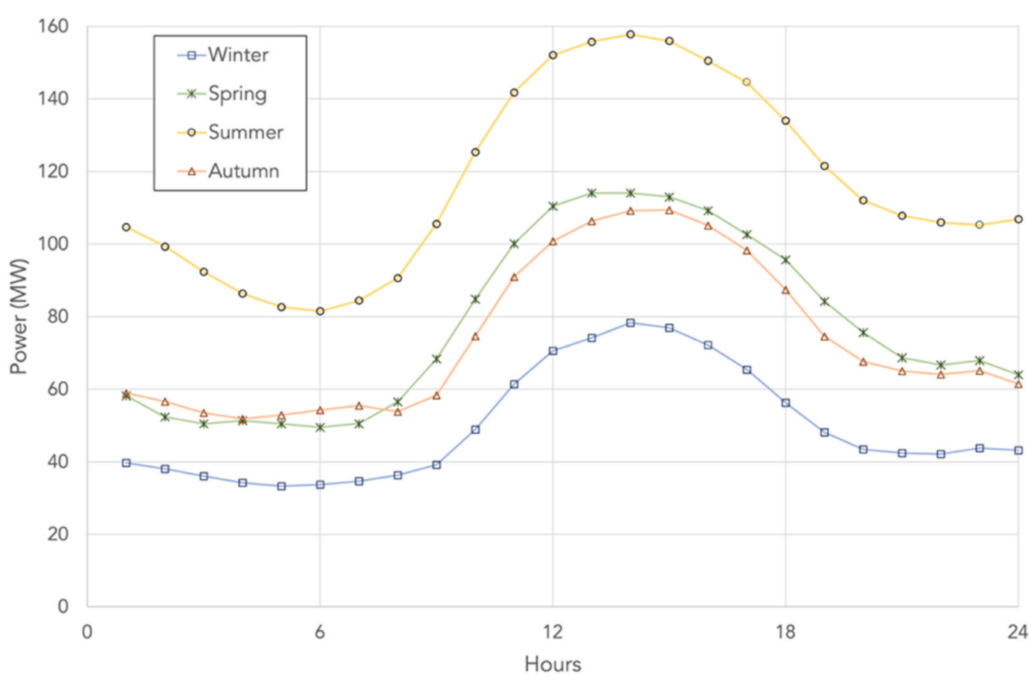


Fig. 1. Average hourly and seasonal onshore renewable power in the ES-GC electrical system (year 2021). Source: ISIOS database of the electrical system operator (REE, n.d.).

et al., 2017). In contrast, during the summer, the average wind speeds in the offshore area of the ES-GC electrical system were mostly in the range between 11 and 12 m/s, which implies a quality of site Excellent-HI (Wind Power Class 7). This speed profile is different from that of the Northern Hemisphere in summer, where the ranges of the areas with wind energy of Class 7 over the westerly oceans are clearly smaller than those in January and April; wind energy over most of the oceans greater than 60°N belongs to Class 3 (Zheng et al., 2017).

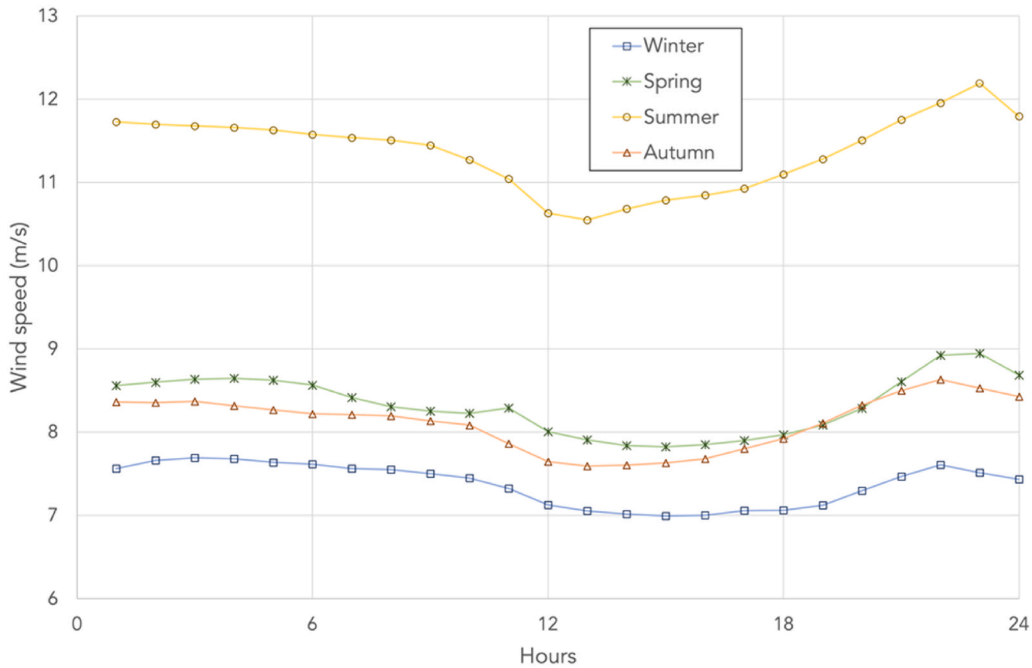


Fig. 2. Profile of the average hourly and seasonal wind speed in the offshore area of the ES-GC electrical system (year 2021). Source: Hersbach et al. (2023).

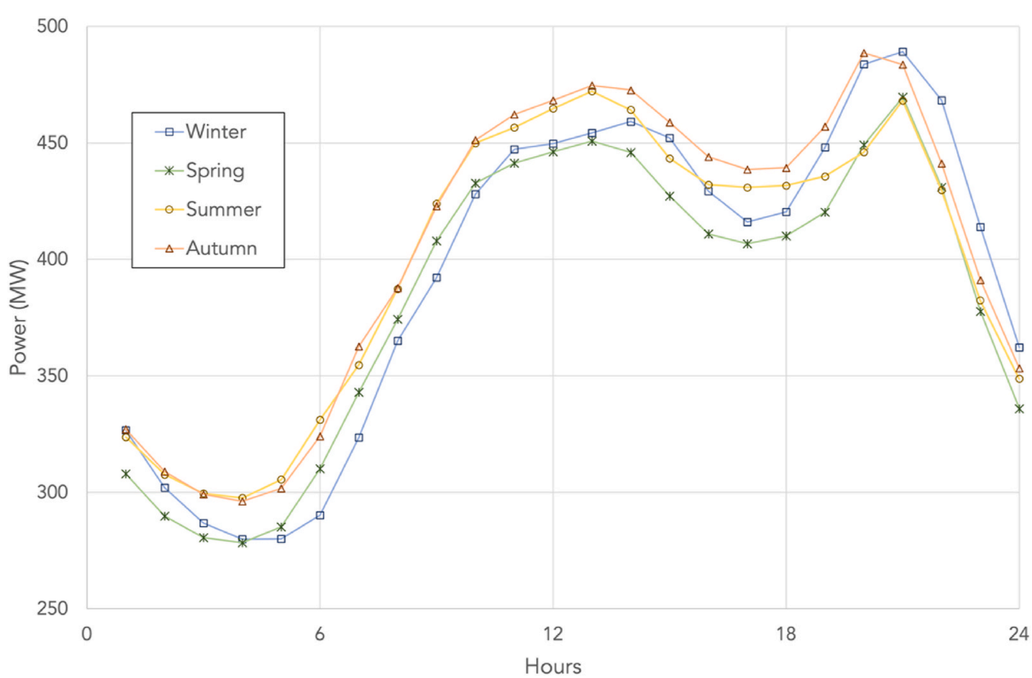


Fig. 3. Profile of the average hourly and seasonal electrical power demand in the ES-GC electrical system (year 2019). Source: ISIOS database of the electrical system operator (REE, n.d.).

The relative influence of the average hourly and seasonal wind speed on the average hourly and seasonal onshore renewable power in the ES-GC electrical system in the year 2021 can be observed in Fig. 1. Although there are differences between offshore and onshore wind speeds, the profiles show the different average contribution of onshore wind farms in the different seasons. Summer, with higher seasonal winds, is the season in which more onshore renewable power was generated in the ES-GC electrical system; in contrast to winter, where the lower average wind speed meant a lower contribution of onshore renewable power. The hourly evolution of the profiles show how the electricity system operator adapted the penetration of onshore renewable power in the ES-GC electrical system to the hourly demand. It should be noted that the profiles in Figs. 1 and 2 can be compared with each other, since they were obtained from data corresponding to the year 2021. However, these profiles cannot be compared with those in Fig. 3, since the latter correspond to electrical power demand data for the year 2019. The electrical power demand for the year 2021 was not taken into consideration due to distortions related to the effects of the Covid-19 pandemic.

Table 3 shows the monthly demand for electrical energy, generation of conventional electrical energy, and onshore renewable electrical energy generation during the years 2019–2021 for the ES-LZFV electrical

Table 3
Monthly evolution of demand and electricity generation in the ES-LZFV electrical system (years 2019–2021). Source: ISIOS database of the electrical system operator (REE, n.d.).

Month	2019			2020			2021		
	Electricity demand (GWh)	Electricity generation from conventional sources (GWh)	Electricity generation from renewable sources (GWh)	Electricity demand (GWh)	Electricity generation from conventional sources (GWh)	Electricity generation from renewable sources (GWh)	Electricity demand (GWh)	Electricity generation from conventional sources (GWh)	Electricity generation from renewable sources (GWh)
January	132.26	123.71	8.55	131.15	122.56	8.60	100.92	91.03	9.89
February	117.30	108.95	8.35	122.64	111.66	10.98	85.48	77.39	8.09
March	127.36	116.63	10.73	113.28	100.66	12.62	94.77	82.85	11.92
April	122.88	107.98	14.90	81.56	72.24	9.32	91.75	82.92	8.83
May	127.20	109.77	17.43	85.08	72.94	12.15	96.79	74.55	22.24
June	127.24	114.00	13.24	87.36	75.48	11.88	99.88	78.53	21.35
July	136.99	114.83	22.17	107.57	88.36	19.21	116.74	87.69	29.05
August	144.25	124.77	19.48	118.90	98.31	20.59	127.54	103.47	24.08
September	136.81	125.59	11.22	108.31	97.40	10.91	125.37	108.78	16.58
October	137.62	126.71	10.91	103.41	92.81	10.60	127.41	111.46	15.95
November	129.15	113.69	15.46	100.22	93.05	7.18	121.20	107.98	13.22
December	130.03	119.87	10.16	104.73	96.03	8.69	124.18	109.95	14.22
Total	1569	1406	163	1264	1121	143	1312	1117	195
Percentage		89.6%	10.4%		88.7%	11.3%		85.1%	14.9%

system. The evolution of this electrical system was similar to that of the ES-GC electrical system, noting that the contributions from renewable energies were higher in the summer months and that the demand for electrical energy has been slowly recovering during the year 2021, after the Covid-19 crisis. The proportion of renewable electrical energy generation has been increasing over the three years considered, growing from 10.4% in 2019 to 14.9% in 2021.

Unlike the demand for electrical power in the ES-GC electrical system, which is quite homogeneous throughout the year, the demand for electrical power in the ES-LZFV electrical system has a more seasonal character. This is largely due to the greater weight of the tourism sector in the economy of the islands that are part of the ES-LZFV electrical system. Fig. 4 shows the evolution of the hourly and seasonal electrical power demand in the ES-LZFV electrical system during 2019. The demand for electrical power increases in the summer months and decreases in the winter months. In turn, just like in the ES-GC electrical system, it experiences significant variations during the hours of the day. Demand was lower in the early hours of the day. The two maximum values of electrical demand occur between 12 and 14 h, and between 19 and 21 h. The most significant difference in the demand for electrical power between the two electrical systems lies in the quantities demanded in each electrical system. The peak demand for electrical power in the ES-LZFV electrical system during 2019 was always lower than the minimum demand for electrical power in the ES-GC electrical system. On average, the demand for electrical power in the ES-GC electrical system was twice as high as the demand for electrical power in the ES-LZFV electrical system. These differences are attributed to the smaller population of the islands that comprise the ES-LZFV electrical system, as well as to their lower economic activity (Institute of Statistics of Canary Islands, 2023a,b).

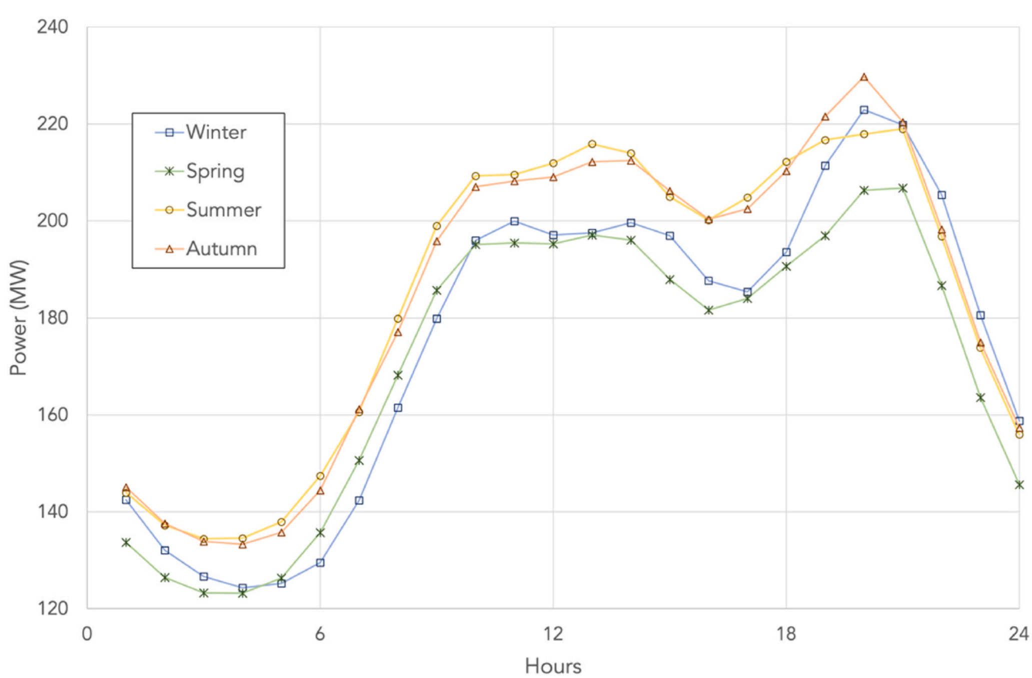


Fig. 4. Profile of the average hourly and seasonal power demand in the ES-LZFV electrical system (year 2019). Source: ISIOS database of the electrical system operator (REE, n.d.).

2.2. Methodology

The information provided by the National Renewable Energy Laboratory (King et al., 2004) was adopted as a reference for calculating the transformation of wind speed into electrical power output in an offshore wind turbine. The power curve corresponding to a normalized generator, as shown in Annex A, was adopted. The losses in the generation, transportation and transformation of the electrical energy generated in the offshore wind turbines, which reduce the electrical energy dumped into the electrical system were evaluated. For this purpose, the study by Musial et al. (2016) was taken as reference, which, based on previous research, established likely minimum and maximum values for losses of 10.6% and 21.3% respectively, corresponding to marine geographic locations at the most and least advantageous extremes for energy recovery. The losses contemplated are as follows: (a) wake losses (4%–12%) arising from effects on wind flow due to interactions between turbines (Musial et al., 2016); (b) Joule losses (1%–5%) in the electrical wires discharging energy into the onshore grid (Beiter et al., 2016); (c) downtime losses (4%) that may be due to adverse weather conditions, technical service problems or the unavailability of land-based infrastructure (Mone et al., 2015); (d) other losses (2%) that may be due to unforeseeable factors, such as facility accidents and underperformance, among others (Beiter et al., 2016). The meteorological data of the offshore wind areas were extracted from the ERA5 databases (Hersbach et al., 2023).

The incorporation of new VRE into an isolated electrical system must comply with a series of limitations. There must be a balance between demand and electrical generation at all times. The demand for electrical energy is considered an input variable and the system operator must cover this demand with different generation technologies. Preferably, renewable energy is incorporated first. Once electrical energy generation through renewable sources is completed, energy from conventional sources must be incorporated.

The security of the electrical supply in isolated systems can be compromised when the penetration of renewables is high (Mohandes et al., 2019). The system operator can limit the contribution of renewable energy to a maximum, in order to always have controllable conventional generators to cover any energy fluctuation. In the electrical systems of the Canary Islands, the reserve to ensure stability is carried out by conventional power plants in most electrical systems, with the range between 20% and 25% of the power demanded (Garcia Latorre et al., 2019). Since practically all the Canary Islands have isolated electrical systems, any configuration with VRE will not be able to supply 100% of the electrical demand securely if the electrical system operator does not have dispatchable (conventional) electrical energy generators or energy storage systems. In the two electrical systems studied (ES-GC and ES-LZFV), there are currently no electrical energy storage systems, with only conventional generators available to ensure the stability of the electrical systems. For calculation purposes, the electricity demand corresponding to the year 2019 has been used as a reference. The reason for using that year as a reference, despite having more recent official demand data, is that the demand for electricity was significantly distorted during the years 2020 and 2021, as a result of the effects on consumption during the Covid 19 pandemic. However, since onshore renewable electrical power has been increasing in recent years, the values corresponding to the year 2021, the last for which official data are available, have been used as a reference for calculation.

To analyze the sizing of offshore wind farms in the case under study, two scenarios have been assumed, without energy storage.

a) with restriction, where 25% of the instantaneous electrical demand is reserved for dispatchable electrical generation (conventional generation);
b) without restriction, where the 25% demand reserve is eliminated. In this latter scenario, renewable sources will be able to meet the total demand for electrical energy.

These two scenarios will be analyzed in three areas of study.

1. The ES-GC electrical system, which comprises the island of Gran Canaria;
2. The ES-LZFV electrical system, which comprises the islands of Fuerteventura and Lanzarote;
3. The existence of a project to interconnect the two electrical systems studied (Lobato et al., 2017) makes it advisable to study the possibility of considering both electrical systems as a single entity (ES-GC and ES-LZFV). This is a project under study by the electrical system operator. The regional government acknowledges in a document on energy transition planning (Government of the Canary Islands, 2022b) that it is not realistic that the option of connecting the ES-GC and ES-LZFV electrical systems by cable can be implemented in the Canary Islands by 2030, since the technical feasibility of this solution has not been demonstrated. However, this possibility is left open in a scenario after that year. In the hypothetical case that the technical feasibility would allow the interconnection of the two electrical systems, taking into account the superior value of offshore wind energy that can be injected into the ES-GC electrical system, only the contribution of offshore wind energy generation from this system will be considered. In turn, in case of interconnection between the two electrical systems, there would be a power limitation in sending electricity from the ES-GC electrical system to the ES-LZFV electrical system defined by the capacity of the submarine cable, which is expected to be 200 MVA.

The incorporation of new offshore wind energy will only be able to displace conventional generation that does not form part of the reserve to maintain supply security. For calculations, the generation of electrical energy through currently existing onshore wind and photovoltaic energy is considered. With these premises, the renewable electrical power obeys Eq. (2):

$$P_{RE} = P_{ON_W} + P_{PH} + P_{OFF_W} \tag{2}$$

where P_{RE} is the renewable electrical power; P_{ON_W} is the onshore wind electrical power; P_{PH} is the electrical power from onshore photovoltaic sources, and P_{OFF_W} is the new offshore wind electrical power that is intended to be added to the electrical system under study.

There can be two situations between electrical supply and demand.

1) Renewable electrical power does not meet the total demanded electrical power.
2) Renewable electrical power exceeds the total demanded electrical power.

2.2.1. Scenario (a). The electrical system operator restricts the penetration of renewable electrical energy (a 25% demand reserve for controllable electrical generation)

The first situation is studied where the renewable electrical power does not cover the total electrical power demanded. Eq. (3) reflects this condition.

$$P_{ED} > P_{RS} + P_{RE} \tag{3}$$

where P_{ED} is the electrical power demanded at a moment; P_{RS} is the reserve electrical power for supply security (25% of P_{ED}); P_{RE} is the existing renewable electrical power at a moment. To maintain the balance between demand and supply of electrical power, a positive value corresponding to conventional electrical power should be added to the inequality, as shown in Eq. (4):

$$P_{ED} = P_{RS} + P_{RE} + P_{CO} \tag{4}$$

where P_{CO} is the conventional electrical power added to the electrical system at a moment. The sum of P_{RS} and P_{CO} is the total conventional electrical power necessary at a moment.

The second situation is studied where the reserve electrical power and the renewable electrical power surpass the total electrical power demanded. Eq. (5) reflects this condition.

$$P_{ED} < P_{RS} + P_{RE} \quad (5)$$

In order to maintain the balance between electrical demand and supply, the electrical power from renewable sources should be reduced until equality is achieved, which can be expressed by Eq. (6):

$$P_{ED} = P_{RS} + \alpha \bullet P_{RE} \quad (6)$$

where the coefficient α represents a value ($0 < \alpha < 1$)) to achieve equality in Eq. (6). The value of the α coefficient represents the fraction of renewable electrical power that can be injected into the electrical system in each hour. This value depends on the existing wind regime (onshore and offshore wind energy), the incidence of solar energy (photovoltaic energy) and the electricity demand. Its behavior does not show a defined evolution as it is influenced by factors independent of each other and with a high hourly and seasonal variability. In relation to the prevailing wind regime in the Canary Islands, higher α coefficient values are expected in the winter months, when wind speeds are, on average, lower; on the contrary, lower α values are expected during the summer months, characterized by higher average wind speeds (Fig. 2). In relation to the incidence of solar energy, lower values of the α coefficient are expected in the central hours of the day, coinciding with the hours of highest insolation. Taking hourly electricity demand as a reference, higher α coefficient values are expected in the central hours of the day and early evening, coinciding with peak electricity demand (Figs. 3 and 4). Through the α coefficient, the renewable electrical power curtailment can be calculated, defined as shown in Eq. (7):

$$P_{EE} = (1 - \alpha) \bullet P_{RE} \quad (7)$$

where P_{EE} is the renewable electrical power curtailment. The value of P_{EE} will directly affect the results of the LCOE calculation for all renewable electricity facilities, causing them to decrease their economic profitability.

2.2.2. Scenario (b). The system operator does not restrict the penetration of renewable electricity

The first situation is studied where the renewable electrical power does not satisfy the total demanded electrical power. Eq. (8) reflects this condition.

$$P_{ED} > P_{RE} \quad (8)$$

To maintain the balance between demand and supply of electrical power, a positive value corresponding to the conventional electrical power must be added to the inequality, as shown in Eq. (9):

$$P_{ED} = P_{RE} + P_{CO} \quad (9)$$

The second situation is studied where the renewable electrical power surpasses the total demanded electrical power. Eq. (10) reflects this condition.

$$P_{ED} < P_{RE} \quad (10)$$

To maintain the balance between demand and supply of electrical power, the electrical power from all renewable sources must be decreased until equality is achieved, which can be expressed by Eq. (11):

$$P_{ED} = \alpha \bullet P_{RE} \quad (11)$$

Where the coefficient α represents a value ($0 < \alpha < 1$) to achieve equality in Eq. (11). Through this coefficient, the renewable electrical power curtailment can be calculated, defined as shown in Eq. (7). Analogously to scenario (a), the renewable electrical power curtailment will directly impact the economic profitability of all renewable energy generation facilities, as it increases the LCOE values.

The impact of offshore wind farms in the three areas of study has been analyzed. The conventional and renewable electrical power data in the two electrical systems considered in 2021 have been adopted (Table 1). To assess the technical and economic efficiency of the new offshore wind energy facilities, it has been considered that these do not have a defined electrical power, but rather a range of electrical power is studied. The new offshore wind farms have been dimensioned in a range from 0 MW to 800 MW. The evaluation of the results has been carried out on an hourly basis, in order to adequately consider the demand and supply data provided by the electrical system operator.

3. Results and discussion

3.1. Study of the ES-GC electrical system

The average annual capacity factor of offshore wind generation in the sea surface linked to the ES-GC electrical system has been evaluated. The power curve of a standardized generator (King et al., 2004), whose reference data are shown in Annex A, has been adopted. The wind speed profile is different each year, so the capacity factor also varies for each year. An average annual capacity factor was obtained for the sea surface linked to the ES-GC electrical system of 42.23% in 2021. This value adequately fits the average capacity factor values of offshore wind facilities analyzed by IRENA (2019).

Fig. 5 shows the variations in the percentage of renewable and conventional electrical energy generation when offshore wind power is added. The ordinate at the origin represents the percentage of onshore renewable energy generation (there is no installed offshore) and conventional generation with the adopted data. As the contribution of offshore electrical power increases, only the percentage of conventional electrical energy generation decreases. The results are shown for the two scenarios (with and without restriction). The results under the restriction scenario never lead to a contribution of renewable electrical energy higher than 60%. However, in the no-restriction scenario, a contribution of renewable electrical energy slightly above 70% can be reached.

Fig. 6 reflects the evolution of the percentage of offshore renewable energy curtailment in the ES-GC electrical system due to the incorporation of new offshore wind power, for the two proposed scenarios. In the first scenario considered, with restriction by the electrical system operator to the penetration of renewable electrical energy, it is observed that there would be an excess of available offshore wind energy starting from 100 MW power in an offshore wind farm. Up to this power value, all generated offshore wind energy could be absorbed by the electrical system. However, in this scenario, if the offshore wind power rose to 200 MW, there would be a percentage of offshore energy curtailment in the system of around 7%. This percentage of offshore energy curtailment would continue to increase as more offshore wind electrical power is added, possibly reaching 58% if an 800 MW offshore wind farm is installed.

In the case that the second scenario is considered, that is, without restriction by the electrical system operator to the penetration of renewable electrical energy, there would not be an excess of available offshore wind energy in the electrical system until a power value of 200 MW offshore wind is reached. From this value, the percentage of offshore energy curtailment would continue to grow up to values around 41% if an 800 MW offshore wind farm is installed.

The regional government's energy strategy envisages the deployment of up to 200 MW of offshore wind power by 2030 for the ES-GC grid (Government of the Canary Islands, 2022a). According to this plan, the offshore wind electrical energy can be incorporated into the system if the electrical system operator eliminates the currently existing restriction on the incorporation of renewable electrical energy. Otherwise, there would be an excess of energy that would have to be utilized through storage in order to avoid shutdowns in the operation of the

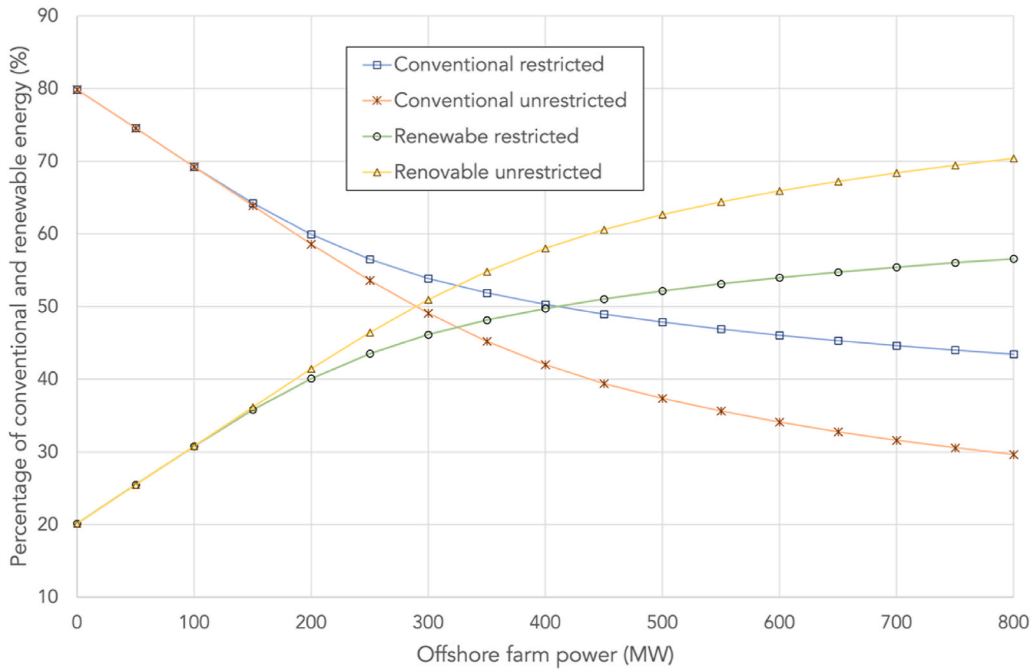


Fig. 5. Percentages of annual electrical energy generation with and without restriction from conventional and renewable energy sources based on the electrical power of the offshore wind farm (Demand in year 2019; Onshore renewable and conventional generation in year 2021) in the ES-GC electrical system.

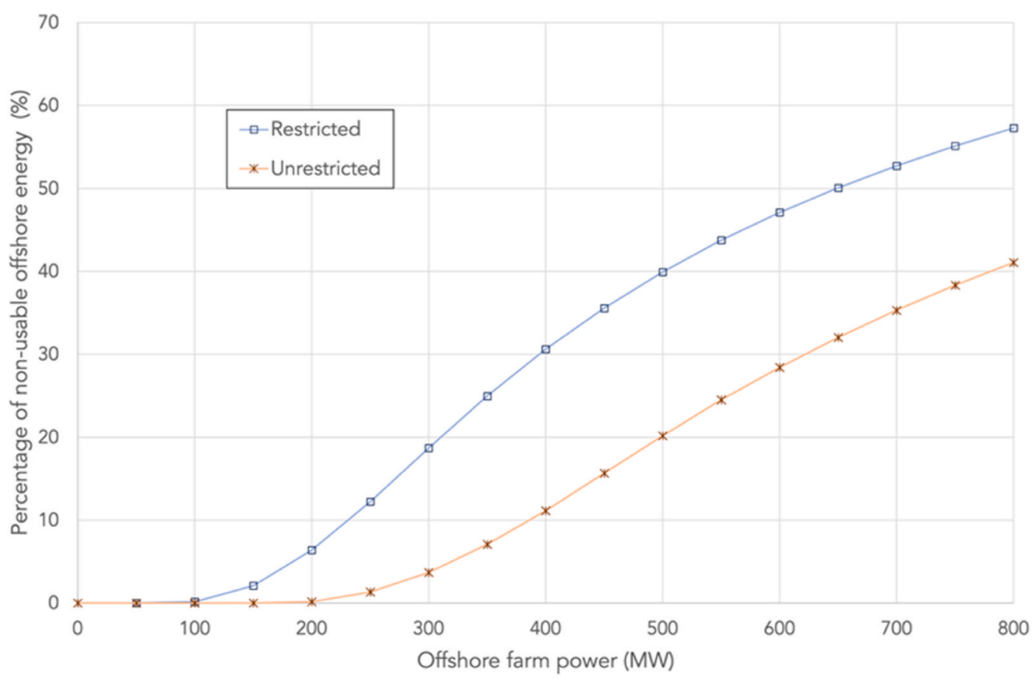


Fig. 6. Percentage of non-useable offshore wind energy with and without restriction in the ES-GC electrical system based on the electrical power of the offshore wind farm (Demand in year 2019; Onshore renewable and conventional generation in year 2021).

offshore wind farm for reasons of network stability. If not, such stoppages would mean less energy generated and, therefore, higher LCOE values. The storage capacity that would be required based on the electrical output of the offshore wind farm can be calculated from the percentages of non-useable offshore energy shown in Fig. 6.

The goal proposed by the regional government of the Canary Islands for the year 2040 raises the offshore wind electrical power in the ES-GC electrical system to 1090 MW. With this data, the percentage of offshore wind energy curtailment would even be higher than calculated.

However, it should be noted that the results in Fig. 6 correspond to annual average values. As shown in Fig. 7, in a scenario without restriction by the electrical operator and with an offshore wind farm of 200 MW power, the highest offshore wind energy curtailment would occur during the spring and summer months. Fig. 8 shows the offshore wind energy curtailment by seasons of the year and by hours of the day. The highest percentage of offshore wind energy curtailment is concentrated in the early hours of the day, when energy demand is lower, and in the months of spring and summer, coinciding with the highest

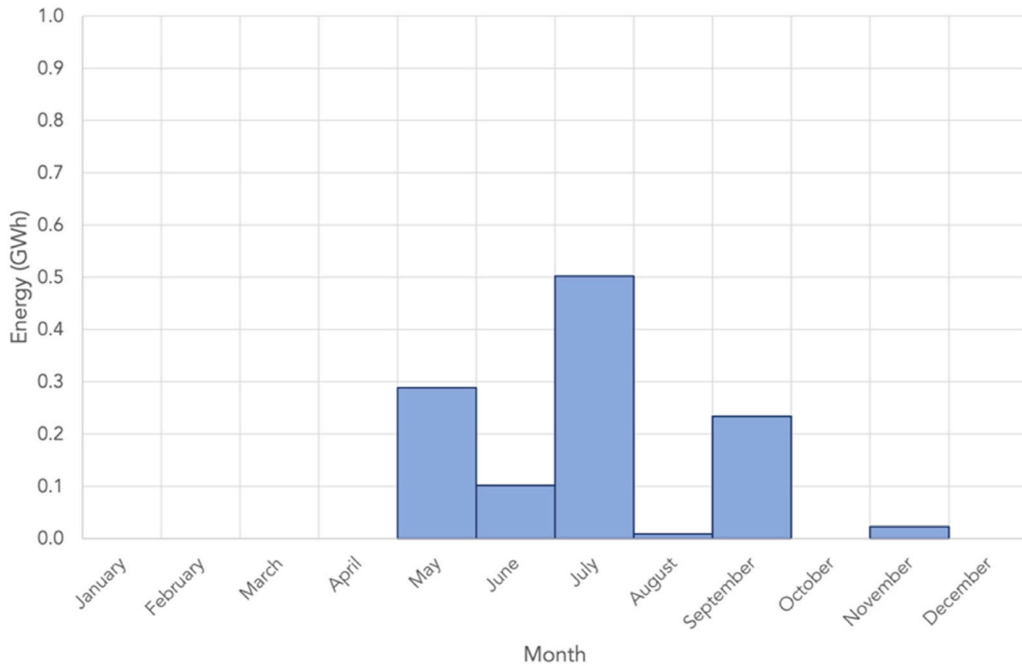


Fig. 7. Monthly offshore wind energy curtailment assuming the operation of a 200 MW offshore wind farm in a scenario without restriction in the ES-GC electrical system.

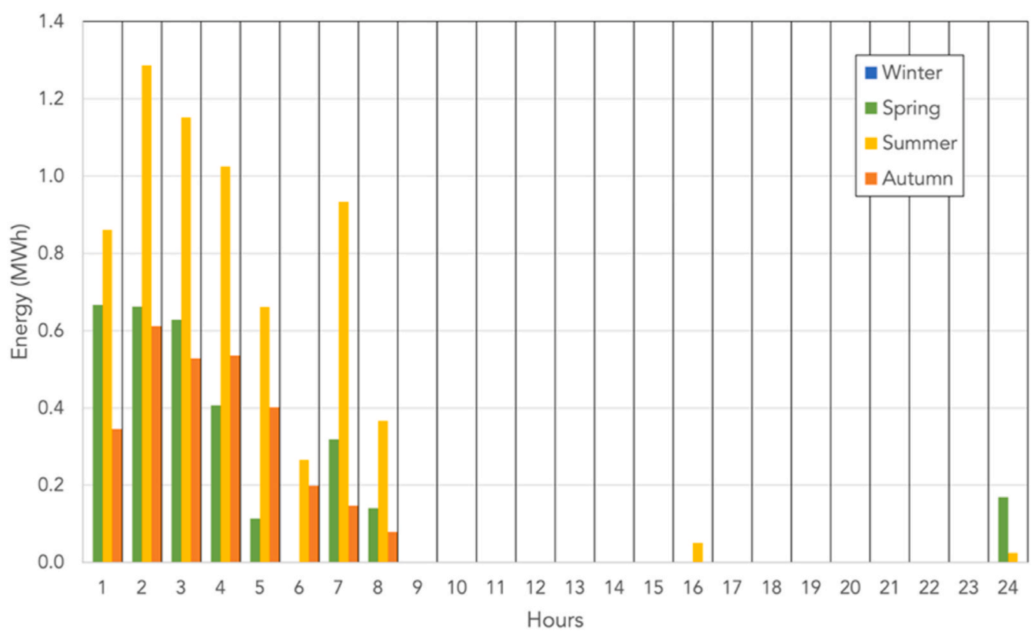


Fig. 8. Seasonal and hourly average offshore wind energy curtailment for a 200 MW offshore wind farm in a scenario without restriction in the ES-GC electrical system.

seasonal wind regime.

3.2. Study of the ES-LZFV electrical system

The average annual capacity factor of offshore wind energy in the sea surface associated with the ES-LZFV electrical system has been evaluated. A standard generator power curve (King et al., 2004), whose reference data are shown in Annex A, was adopted. The wind speed profile is different each year, therefore, the capacity factor also varies each year. An average annual capacity factor for the sea surface corresponding to the ES-LZFV electrical system of 43% was obtained in 2021. This value is adequately adjusted to the average capacity factor values of the offshore wind facilities analyzed by (IRENA, 2019).

Fig. 9 shows the results when new offshore wind electrical power is added to the ES-LZFV. The incorporation of new offshore wind farms could lead to a decrease in conventional generation from 88% to 24% in a scenario without restriction by the electrical system operator.

In Fig. 10, for the two scenarios considered (with and without restriction), the results on the percentage of offshore wind energy curtailment are shown as a function of the electrical power of a new offshore wind farm. Under the scenario of security restriction in the supply of electrical energy, a percentage of offshore energy curtailment

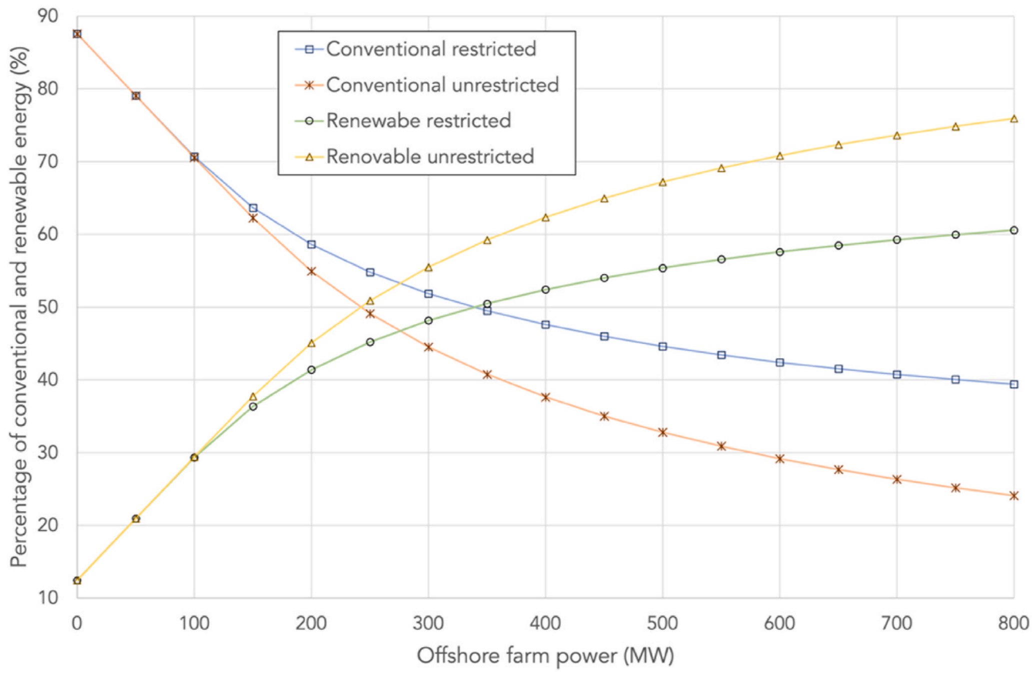


Fig. 9. Percentages of annual electrical energy generation with and without restriction from conventional and renewable energy sources based on the electrical power of the offshore wind farm (Demand in year 2019; Onshore and conventional renewable generation in year 2021) in the ES-LZFV electrical system.

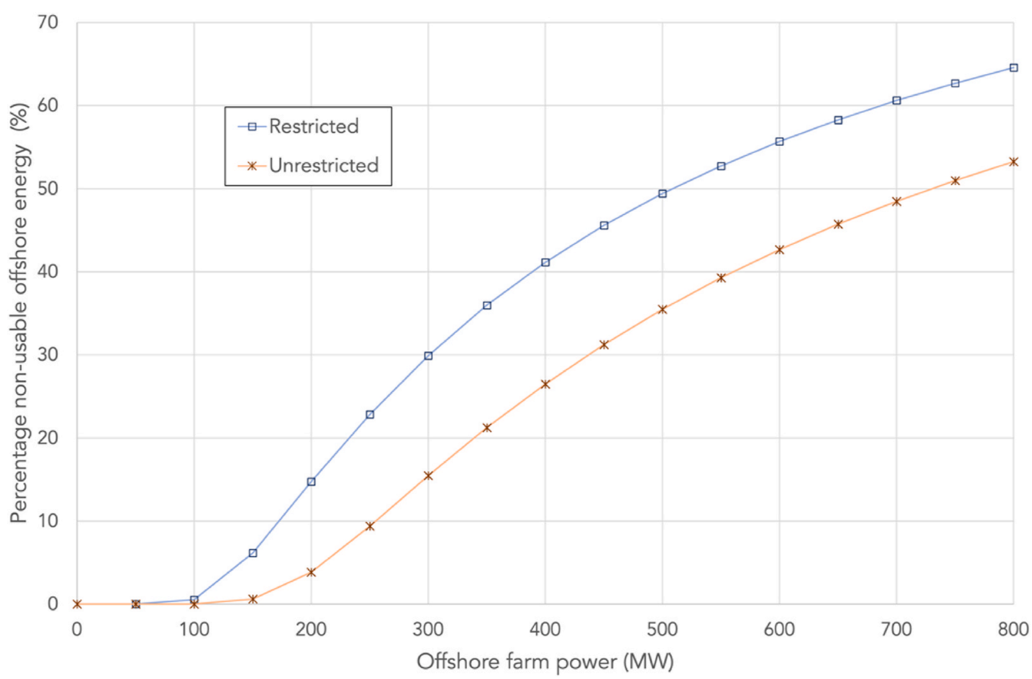


Fig. 10. Percentage of non-useable offshore wind energy with and without restriction in the ES-LZFV electrical system based on the electrical power of the offshore wind farm (Demand in year 2019; Onshore renewable and conventional generation in year 2021).

begins to appear with a 50 MW offshore wind farm. In the scenario without restriction, the percentage of offshore wind energy curtailment arises when the offshore wind farm reaches 100 MW. It can be inferred that, for an 800 MW offshore wind farm, a percentage of offshore energy curtailment of about 64% can be produced in a scenario with restriction, and 53% in the scenario of no restriction.

The regional government's energy strategy envisages the deployment of up to 100 MW of offshore wind power by 2030 for the ES-LZFV grid (Government of the Canary Islands, 2022a). According to this plan, a percentage of offshore energy curtailment of less than 1% would occur, assuming a scenario with restriction. However, in the second scenario, without restriction from the electrical system operator to the penetration of renewable electrical energy, there would be no percentage of offshore wind energy curtailment in the ES-LZFV electrical system. The planning of the regional government of the Canary Islands for the year 2040 includes the installation of 860 MW of electrical power in offshore wind farms in the ES-LZFV electrical system (Government of the Canary Islands, 2022a). With these values, the percentage of offshore energy curtailment would be higher than 50% in both scenarios, as shown in Fig. 10.

3.3. Study of the interconnected ES-GC and ES-LZFV electrical systems

The electrical energy currently generated in the ES-GC electrical system is much higher than that generated in the ES-LZFV electrical system. If both systems were interconnected, it could happen that the ES-GC electrical system would provide all the electrical energy demanded by the ES-LZFV electrical system. In this case, the capacity of the interconnection cable (200 MVA) is the factor that limits the power that can be supplied to the ES-LZFV electrical system from the ES-GC electrical system. In case of interconnection, if the electrical energy required by the ES-LZFV electrical system would be greater than what could be conveyed by the cable, it would be necessary to provide conventional or renewable electrical energy from the ES-LZFV electrical system itself.

Fig. 11 shows the variations in the percentages of conventional and renewable electrical generation in the case of the two electrical systems being interconnected and the electricity from a hypothetical offshore wind farm with different power values being added. Assuming an 800 MW offshore wind farm, the penetration of renewables would be around 53% in the restriction scenario and around 64% in the no restriction scenario.

Fig. 12 shows, for the two scenarios considered, the results on the percentage of offshore wind energy curtailment as a function of the electrical power of a new offshore wind farm which discharges energy into the ES-GC electrical system and it is connected to the two linked electrical systems. Under the scenario of safety restriction in the supply of electrical energy, a percentage of offshore energy curtailment arises with a 200 MW offshore wind farm. However, in the scenario of no restriction, the percentage of offshore energy curtailment arises with a 300 MW offshore wind farm. It can be inferred that for an 800 MW offshore wind farm, the percentage of offshore wind curtailment could increase to around 40.5% in the restriction scenario and around 22% in the no restriction scenario. These values are lower than those obtained considering the two electrical systems isolated from each other. Therefore, the project to connect both electrical systems, if technically feasible, would result in a higher penetration of renewable energy.

The energy strategy of the regional government envisages the deployment of 300 MW of offshore wind electrical power for the year 2030 combining the two electrical systems. It can be deduced that in a scenario of restriction by the electrical operator, there would be an offshore wind energy curtailment percentage of around 4%. On the contrary, in the case of no restriction by the electrical operator, the regional government's planning for 2030 would coincide with the value at which, on average, there would be no offshore wind energy curtailment percentage. In the case of the planning expected for 2040, with a total of 1950 MW of offshore wind electrical power between both electrical systems, the percentage of offshore energy curtailment would exceed the calculated, which has been carried out considering a maximum installation of 800 MW of electrical power in offshore wind farms.

3.4. Influence of the offshore wind energy curtailment percentage on the LCOE

The response of the electrical operator of the Canary Islands when there are episodes of available renewable energy that cannot be injected into the electrical grid is to stop the operation of existing onshore wind or photovoltaic farms. In this situation, the energy curtailment that would occur in the analyzed electrical systems as a result of incorporating offshore wind energy would be a loss because it could not be incorporated into the system. As a result, not only would the technical performance of the new offshore facilities be affected, but also the economic performance. Eq. (1) reflects that, in the case of investment in offshore wind farms, the numerator remains unchanged due to the existence of fixed and variable operating costs that do not change even when no energy is generated. In this case, as the wind is the primary energy source, there are no variable costs for the consumption of primary energy, as is the case with conventional facilities. Eq. (1) also shows that the denominator decreases when the annual electricity injected into the system is reduced by the presence of an offshore energy curtailment. These circumstances lead to an increase in the LCOE, which could represent a significant obstacle to investment in offshore wind farms, thus reducing their competitiveness against conventional generation facilities.

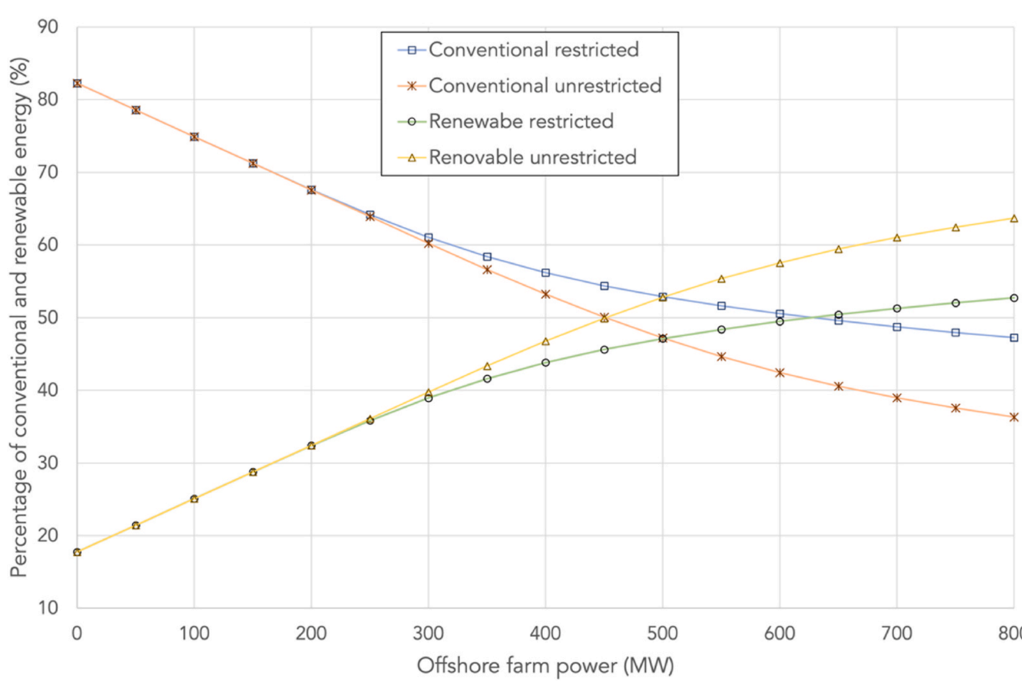


Fig. 11. Percentages of annual electrical energy generation with and without restriction from conventional and renewable energy sources based on the electrical power of the offshore wind farm (Demand in year 2019; Onshore and conventional renewable generation in year 2021) in the interconnected electrical systems.

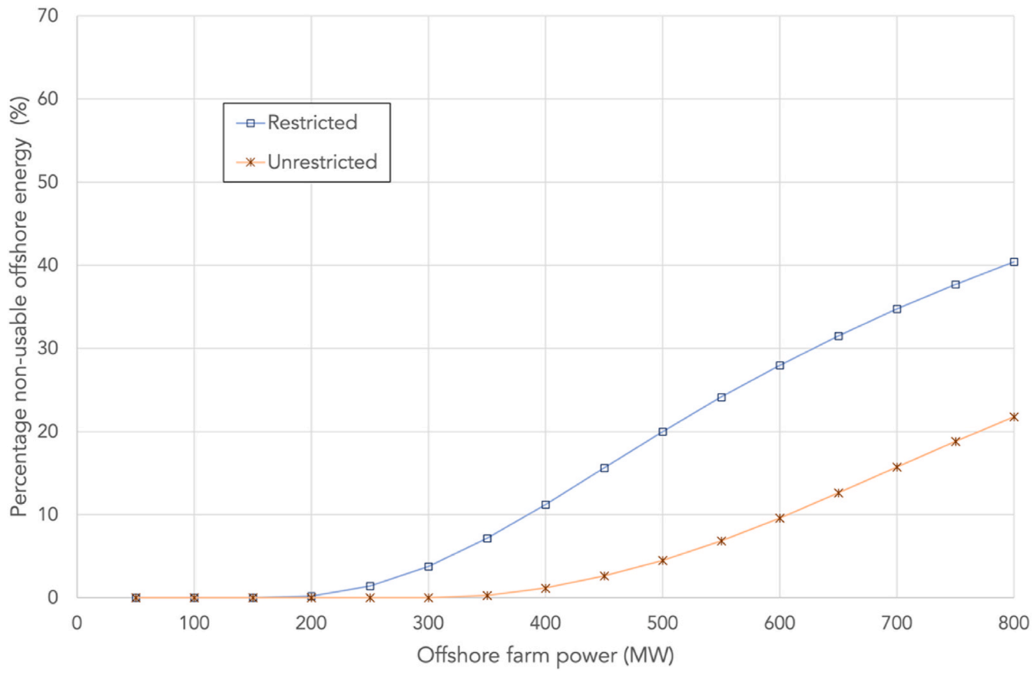


Fig. 12. Percentage of non-useable offshore wind energy with and without restriction, assuming interconnected electrical systems, based on the electrical power of the offshore wind farm (Demand in year 2019; Onshore and conventional renewable generation in year 2021).

Relating Eq. (1) to the results obtained, it is possible to deduce the evolution of the increase in LCOE based on the percentage of offshore wind energy curtailment. As shown in Fig. 13, when all offshore wind energy is utilized, there is no increase in the value of the LCOE of the facility. On the contrary, as the percentage of offshore wind energy curtailment increases, the value of the LCOE increases. Knowing the shape followed by this evolution can be a relevant source of information for calculating the new offshore wind electrical power to be installed. However, this increasing evolution of the LCOE could be mitigated if energy storage systems were incorporated into the electrical systems. Even so, the LCOE would increase because the costs of investment, operation, maintenance and decommissioning of the storage systems must be included in the LCOE calculation.

Table 4 summarizes the economic implications of incorporating new offshore wind farms into the electrical systems of the territory studied. Different electrical powers of the offshore wind farms in the ES-GC electrical system, the ES-LZFV electrical system, and the joint electrical system assuming a connection cable between both (ES-GC and ES-LZFV) are considered. Depending on the electrical power, percentage values of offshore wind energy curtailment are obtained under the consideration of a scenario with restriction or without restriction. Likewise, depending on the electrical power, LCOE increment factors are

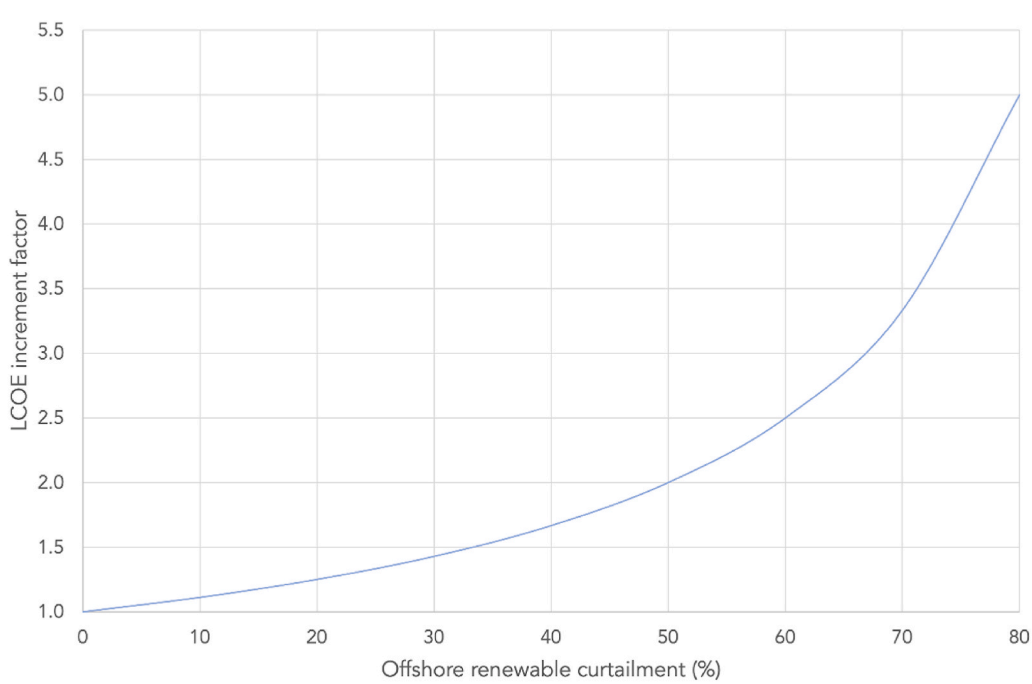


Fig. 13. Increase factor of the LCOE based on the percentage of offshore wind energy curtailment.

Table 4
Economic implications for the LCOE due to offshore wind energy curtailment.

Offshore wind farm electrical power (MW)	Percentage of offshore energy curtailment (%)		LCOE increment factor		Reference costs of floating offshore wind energy				Average cost of electrical generation through conventional energy (€/MWh)
					LCOE estimated in the study by Aldersey-Williams and Rubert (2019) 50,00 (€/MWh)		LCOE estimated in the study by Clauser and Ewert (2018) 172,00 (€/MWh)		
	RSc	USc	RSc	USc	RSc	USc	RSc	USc	
200 (ES-GC)	6.40	0.16	1.07	1.00	53.42	50.08	183.76	172.28	153.98
100 (ES-LZFV)	0.55	0.00	1.01	1.00	50.28	50.00	172.95	172.00	166.81
300 (ES-GC-LZFV)	3.79	0.01	1.04	1.00	51.97	50.01	178.78	172.02	153.98

RSc: Restricted Scenario.
USc: Unrestricted Scenario.

obtained under the consideration of a scenario with or without restriction. These LCOE increment factor values are used as a multiplier for the LCOE values obtained in the studies by Aldersey-Williams and Rubert (2019), and Clauser and Ewert (2018). These studies were chosen as a reference because they reflect the lowest and highest estimates of the LCOE for floating[1] offshore wind farms among the consulted literature. These extreme values of LCOE estimates represent the most and least favorable ranges for comparing the cost of conventional energy with the cost of floating offshore wind energy. The obtained values, under the consideration of a scenario with or without restriction, are compared with the average cost of electricity generation through conventional energy that would be displaced by offshore wind energy.[2] Adopting the LCOE values from the study by Aldersey-Williams and Rubert (2019), the deployment of offshore wind farms could mean generating electricity at costs lower than those of electrical generation using conventional facilities. However, according to the estimates from the study by Clauser and Ewert (2018), the installation of offshore wind farms could mean generating electricity at costs higher than those of electricity generation using conventional energy.

Spanish citizens pay the same amount for electricity regardless of their place of residence. In the case of the territory under study, electricity prices are subsidized. Table 5 shows the average electricity prices in Spain during the years 2017–2021. A certain homogeneity in average prices can be observed during the period from 2017 to 2019. In 2020 there was a decrease in the average price compared to previous years as a result of lower electricity demand due to the effects of the Covid-19 pandemic. In 2021, there was a growth in prices due to the incipient post-pandemic economic recovery and the shortage of oil supply in international markets. Comparing the values of the average cost of electricity generation through conventional energy and the values in Table 5, electricity consumers in the ES-GC and ES-LZFV electrical systems pay a price for electricity lower than the costs of conventional generation. Thus, the subsidy is mainly intended to compensate for conventional electricity generation costs; that is, it primarily compensates for the consumption of fossil fuels as primary energy. Given this situation, a political action could be to gradually allocate this subsidy to promote investment in renewable energies and storage systems, thereby contributing to achieving decarbonization objectives.

Table 5
Average annual electricity price in Spain from 2017 to 2021. Source: own elaboration based on Statista (2023).

2017 (€/MWh)	2018 (€/MWh)	2019 (€/MWh)	2020 (€/MWh)	2021 (€/MWh)
60.55	64.37	53.41	40.37	118.7

In view of the results obtained, technical and economic implications have become evident that point to aspects that should be considered in the energy policy of island territories with isolated electrical systems that are planning the deployment of offshore wind energies. Offshore wind energy brings with it problems of penetration capacity in these electrical systems. Moreover, due to its high variability, offshore wind energy will not be able to satisfy 100% of the demand all the time in these territories. The seasonality of offshore wind regimes and the profile of energy demand make greater penetration difficult, forcing the recovery of non-useable offshore energy for other energy purposes. These include energy storage. It is also necessary to have dispatchable energy sources for those cases in which, due to weather conditions, there is no offshore wind energy generation for long periods of time. It would be a matter of achieving a balance between, on the one hand, the appropriate sizing of this type of facilities to minimize energy curtailments that imply an increase in the LCOE, and, on the other hand, investing in massive energy storage systems that allow the surplus of offshore wind energy to be used, although this investment also translates into an increase in the LCOE.

Both options, however, entail an increase in the LCOE for this type of investment. It is therefore necessary to articulate public policies aimed at mitigating this extra cost, while striking a balance between the public interest in developing clean energy and the cost to the public purse. The results show that offshore wind energy can have a higher cost than existing energy costs, based primarily on fossil fuels. However, to achieve the goal of independence from fossil energy in isolated systems, the incorporation of new renewable sources must be encouraged, and subsidies can be a mechanism that contributes to this goal. Subsidies have been used before by public institutions, for example, to support investment in onshore wind or photovoltaic installations.

4. Conclusions and policy implications

In previous sections, estimated values of offshore wind energy penetration have been obtained for an isolated island territory where the main source of electrical generation is fossil fuels. In the three scenarios analyzed, the percentage of non-useable offshore wind energy is higher for the isolated systems compared to the interconnected system. In the two interconnected electrical systems considered (ES-GC and ES-LZFV) and with an 800 MW offshore wind farm, it would be possible to achieve renewable energy penetration of up to 65% of the total annual electricity demand. The estimated percentage of offshore wind energy

[1] The optimal maritime areas for the location of offshore wind farms, identified in the study by Díaz and Soares (2021), to inject energy into the electrical systems analyzed imply the need to incorporate floating offshore wind technology due to their great depths.

[2] The average cost of conventional electrical generation in 2021 was €153.98/MWh for the ES-GC system, and €166.81/MWh for the ES-LZFV system (Government of the Canary Islands, 2023).

curtailment as a result of the deployment of offshore wind farms under the conditions and scenarios considered in the study has also been evaluated.

The adopted case study shows that a 100% electricity generation from renewable sources in small isolated electrical systems cannot be achieved without electricity storage systems that allow the storage of the surplus, while stabilizing the electricity distribution network. This is due to the seasonal and hourly fluctuations of VRE, coupled with the variability of electricity demand. A consequence of this situation is an increase in the LCOE due to the increase in the percentage of offshore wind energy curtailment. An increase in the LCOE involves a loss of attractiveness for investment in this type of facility. This loss of attractiveness could be neutralized through the intervention of governments (regional and national) to offset the costs associated with offshore wind energy generation.

Taking into account the results obtained, and with the aim of achieving decarbonization objectives, government action could support investment in offshore wind energy through energy policies. Public institutions could.

1) Promote the development, in parallel to the investment in offshore wind farms, of massive energy storage systems that store the offshore wind energy curtailment.
2) Rethink the objectives of offshore wind energy penetration so that installed power does not exceed a threshold that implies the existence of offshore wind energy curtailment in the event that massive energy storage systems are not developed in parallel.
3) Analyze the suitability of implementing different financial and fiscal instruments by public institutions to promote investment in offshore wind energy technologies.
4) Consider the potential investment in the installation of a submarine electrical cable connecting the ES-GC and ES-LZFV electrical systems, assuming interconnection is technically feasible in the future.
5) Upgrade existing power facilities that use conventional generation systems with greater flexibility and response speed to generate electricity in conjunction with renewable energy sources.
6) Explore investment in new renewable energy sources such as tidal, wave, geothermal, etc.
7) Utilize surplus offshore wind energy for the production of other types of complementary fuels (e.g. LPG, H_2) for use in land and maritime transportation.

This study has analyzed a specific territory, which constitutes a limitation in terms of generalizing the results. However, the high similarity in the problems presented by island territories with small isolated electrical systems allows the method of analysis proposed in this study to be applied to them. In such a case, as a future line of research, the results obtained in other territories could be compared and alternative energy policies emerge. Another line of research proposed, for its contribution to evaluate the LCOE of the investment in floating offshore wind energy projects, would be the comparison of energy storage costs with non-useable offshore energy prices.

CRediT authorship contribution statement

Moisés Martín-Betancor: Formal analysis, Resources, Software, Visualization. **Javier Osorio:** Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing. **Alejandro Ruíz-García:** Validation, Writing – original draft, Writing – review & editing. **Ignacio Nuez:** Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

Javier Osorio reports financial support was provided by European Regional Development Fund. Javier Osorio reports a relationship with European Regional Development Fund that includes: funding grants.

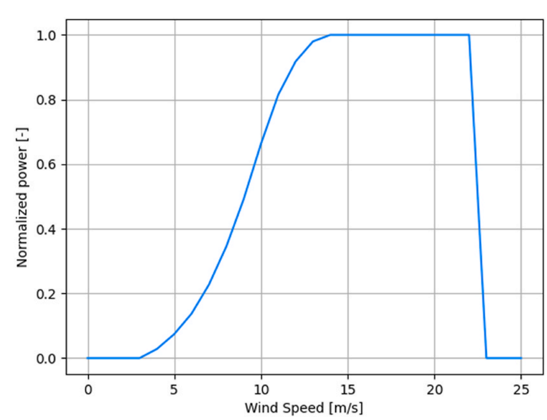
Data availability

Data will be made available on request.

Acknowledgments

This work was partially funded by the ACLIEMAC (MAC2/3.5b/380) project with the support of the European Union (EU), and co-financed through the European Regional Development Fund (ERDF) and INTERREG V-A MAC 2014–2020.

Appendix A. Power curve and key parameters for a standard wind turbine. Source: (King et al., 2004)



Item	Value	Units
Name	WTK Validation Offshore	N/A
Rated Power		kW
Rated Wind Speed	14	m/s
Cut-in Wind Speed	4	m/s
Cut-out Wind Speed	25	m/s
Rotor Diameter		m
Hub Height		m
Drivetrain		N/A
Control		N/A
IEC Class		N/A

Normalized offshore power curve comes from a report validating power output for the WIND Toolkit 1. The report presents normalized power curves but assumes 100 m hub heights for modeling in the report. Cp values are not available since rotor diameters are not included.

References

Abramic, A., García Mendoza, A., Haroun, R., 2021. Introducing offshore wind energy in the sea space: canary Islands case study developed under Maritime Spatial Planning principles. Renew. Sustain. Energy Rev. 145, 111119 https://doi.org/10.1016/j.rser.2021.111119.

Ahn, E., Hur, J., 2022. A practical Metric to evaluate the ramp events of wind generating Resources to enhance the security of smart energy systems. Energies 15, 2676. https://doi.org/10.3390/en15072676.

Aldersey-Williams, J., Rubert, T., 2019. Levelised cost of energy – a theoretical justification and critical assessment. Energy Pol. 124, 169–179. https://doi.org/10.1016/j.enpol.2018.10.004.

Al-Shetwi, A.Q., Hannan, M.A., Jern, K.P., Mansur, M., Mahlia, T.M.I., 2020. Grid-connected renewable energy sources: review of the recent integration requirements and control methods. J. Clean. Prod. 253, 119831 https://doi.org/10.1016/j.jclepro.2019.119831.

Barter, G.E., Robertson, A., Musial, W., 2020. A systems engineering vision for floating offshore wind cost optimization. Renewable Energy Focus 34, 1–16. https://doi.org/10.1016/j.ref.2020.03.002.

Beiter, P., Musial, W., Smith, A., Kilcher, L., Damiani, R., Maness, M., Sirnivas, S., Stehly, T., Gevorgian, V., Mooney, M., Scott, G., 2016. A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030. https://doi.org/10.2172/1324526. United States.

Branker, K., Pathak, M.J.M., Pearce, J.M., 2011. A review of solar photovoltaic levelized cost of electricity. Renew. Sustain. Energy Rev. 15, 4470–4482. https://doi.org/10.1016/j.rser.2011.07.104.

Chang, C.A., Wu, Y.K., Chen, B.K., 2016. Determination of maximum wind power penetration in an isolated island system by considering spinning reserve. Energies 9. https://doi.org/10.3390/en9090688.

Chen, P., Hu, Z., 2022. Analysis of key disciplinary parameters in floating offshore wind turbines with an AI-based SADA method. China Ocean Eng. 36, 649–657. https://doi.org/10.1007/s13344-022-0045-4.

Clauser, C., Ewert, M., 2018. The renewables cost challenge: levelized cost of geothermal electric energy compared to other sources of primary energy – review and case study. Renew. Sustain. Energy Rev. 82, 3683–3693. https://doi.org/10.1016/j.rser.2017.10.095.

Denholm, P., Hand, M., 2011. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Pol. 39, 1817–1830. https://doi.org/10.1016/j.enpol.2011.01.019.

Díaz, H., Soares, C.G., 2021. A multi-criteria approach to evaluate floating offshore wind farms siting in the canary islands (Spain). Energies 14, 865. https://doi.org/10.3390/en14040865.

European Court of Auditors, 2017. EU Action on Energy and Climate Change. https://doi.org/10.2865/929963.

Feng, C.-C., Chang, K.-F., Lin, J.-X., Lee, T.-C., Lin, S.-M., 2022. Toward green transition in the post Paris Agreement era: the case of Taiwan. Energy Pol. 165, 112996 https://doi.org/10.1016/j.enpol.2022.112996.

Garcia Latorre, F.J., Quintana, J.J., de la Nuez, I., 2019. Technical and economic evaluation of the integration of a wind-hydro system in El Hierro island. Renew. Energy 134, 186–193. https://doi.org/10.1016/j.renene.2018.11.047.

Government of the Canary Islands, 2023. Anuario Energético de Canarias 2021.

Government of the Canary Islands, 2022a. Estrategia de las energías renovables marinas de Canarias [WWW Document]. https://www.gobiernodecanarias.org/energia/materias/planificacion/.

Government of the Canary Islands, 2022b. Plan de Transición Energética de Canarias PTECan-2030 [WWW Document]. https://www.gobiernodecanarias.org/energia/materias/planificacion/.

Heetun, K.Z., Abdel Aleem, S.H.E., Zobaa, A.F., 2016. Voltage stability analysis of grid-connected wind farms with FACTS: static and dynamic analysis. Energy Policy Res. 3, 1–12. https://doi.org/10.1080/23317000.2015.1128369.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J.-N., 2023. ERA5 hourly data on single levels from 1940 to present. In: Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.adbb2d47 [WWW Document].

IEA, 2019. World Energy Outlook 2019.

Institute of Statistics of Canary Islands, 2023a. Población turística equivalente. Islas y municipios de Canarias por periodos [WWW Document]. https://www3.gobiernodecanarias.org/istac/statistical-visualizer/visualizer/data.html?resourceType=dataset&agencyId=ISTAC&resourceId=C00065A_000041&version=1.0.

Institute of Statistics of Canary Islands, 2023b. Población según sexos. Municipios por islas de Canarias y años [WWW Document]. https://www3.gobiernodecanarias.org/istac/statistical-visualizer/visualizer/data.html?resourceType=dataset&agencyId=ISTAC&resourceId=E30245A_000002&version=1.2#visualization/table.

IRENA, 2022. Renewable Capacity Statistics 2022.

IRENA, 2019. Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects (A Global Energy Transformation Paper).

Johnson, S.C., Rhodes, J.D., Webber, M.E., 2020. Understanding the impact of non-synchronous wind and solar generation on grid stability and identifying mitigation pathways. Appl. Energy 262, 114492. https://doi.org/10.1016/j.apenergy.2020.114492.

Johnston, B., Foley, A., Doran, J., Littler, T., 2020. Levelised cost of energy, A challenge for offshore wind. Renew. Energy 160, 876–885. https://doi.org/10.1016/j.renene.2020.06.030.

King, J., Clifton, R.A., Hodge, B.-M., 2004. Validation of Power Output for the WIND Toolkit.

Lerch, M., De-Prada-Gil, M., Molins, C., Benveniste, G., 2018. Sensitivity analysis on the levelized cost of energy for floating offshore wind farms. Sustain. Energy Technol. Assessments 30, 77–90. https://doi.org/10.1016/j.seta.2018.09.005.

Lobato, E., Sigrist, L., Rouco, L., 2017. Value of electric interconnection links in remote island power systems: the Spanish Canary and Balearic archipelago cases. Int. J. Electr. Power Energy Syst. 91, 192–200. https://doi.org/10.1016/j.ijepes.2017.03.014.

Loth, E., Qin, C., Simpson, J.G., Dykes, K., 2022. Why we must move beyond LCOE for renewable energy design. Adv. Appl. Energy 8, 100112. https://doi.org/10.1016/j.adapen.2022.100112.

Maienza, C., Avossa, A.M., Ricciardelli, F., Coiro, D., Troise, G., Georgakis, C.T., 2020. A life cycle cost model for floating offshore wind farms. Appl. Energy 266, 114716. https://doi.org/10.1016/j.apenergy.2020.114716.

Martinez, A., Iglesias, G., 2022. Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic. Renew. Sustain. Energy Rev. 154, 111889 https://doi.org/10.1016/j.rser.2021.111889.

Mohandes, B., Moursi, M.S. El, Hatziargyriou, N., Khatib, S. El, 2019. A review of power system flexibility with high penetration of renewables. IEEE Trans. Power Syst. 34, 3140–3155. https://doi.org/10.1109/TPWRS.2019.2897727.

Mone, C., Stehly, T., Maples, B., Settle, E., 2015. 2014 Cost of Wind Energy Review. United States. https://doi.org/10.2172/1225925.

Musial, W., Heimiller, D., Beiter, P., Scott, G., Draxl, C., 2016. 2016 Offshore Wind Energy Resource Assessment for the United States.

Musial, W., Spitsen, P., Duffy, P., Beiter, P., Marquis, M., Hammond, R., Shields, M., 2022. Offshore Wind Market Report: 2022 Edition. United States. https://doi.org/10.2172/1883382.

Pandey, S.K., Mohanty, S.R., Kishor, N., 2013. A literature survey on load–frequency control for conventional and distribution generation power systems. Renew. Sustain. Energy Rev. 25, 318–334. https://doi.org/10.1016/j.rser.2013.04.029.

Partridge, I., 2018. Cost comparisons for wind and thermal power generation. Energy Pol. 112, 272–279. https://doi.org/10.1016/j.enpol.2017.10.006.

Pires, A.L.G., Junior, P.R., Morioka, S.N., Rocha, L.C.S., Bolis, I., 2022. Main trends and criteria adopted in economic feasibility studies of offshore wind energy: a systematic literature review. Energies. https://doi.org/10.3390/en15010012.

REE, REE. Spanish System Operator n.d. [WWW Document] https://www.esios.ree.es/es.

Reichenberg, L., Hedenus, F., Odenberger, M., Johnsson, F., 2018. The marginal system LCOE of variable renewables – evaluating high penetration levels of wind and solar in Europe. Energy 152, 914–924. https://doi.org/10.1016/j.energy.2018.02.061.

Schallenberg-Rodríguez, J., García Montesdeoca, N., 2018. Spatial planning to estimate the offshore wind energy potential in coastal regions and islands. Practical case: the Canary Islands. Energy 143, 91–103. https://doi.org/10.1016/j.energy.2017.10.084.

Shen, W., Chen, X., Qiu, J., Hayward, J.A., Sayeef, S., Osman, P., Meng, K., Dong, Z.Y., 2020. A comprehensive review of variable renewable energy levelized cost of electricity. Renew. Sustain. Energy Rev. 133, 110301 https://doi.org/10.1016/j.rser.2020.110301.

Sklar-Chik, M.D., Brent, A.C., De Kock, I.H., 2018. Integration costs of renewable energy technologies in future energy generation scenarios. S. Afr. J. Ind. Eng. 29, 28–42. https://doi.org/10.7166/29-2-1801.

Statista, 2023. Precio Medio final anual de la electricidad en España de 2010 a 2022 [WWW Document]. https://es.statista.com/estadisticas/993787/precio-medio-final-de-la-electricidad-en-espana/.

Tamrakar, U., Shrestha, D., Maharjan, M., Bhattarai, B.P., Hansen, T.M., Tonkoski, R., 2017. Virtual Inertia: Current Trends and Future Directions. Appl. Sci. https://doi.org/10.3390/app7070654.

The European Parliament and the Council of the European Union, 2023. Fit for 55 [WWW Document]. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

Tran, T.T.D., Smith, A.D., 2018. Incorporating performance-based global sensitivity and uncertainty analysis into LCOE calculations for emerging renewable energy technologies. Appl. Energy 216, 157–171. https://doi.org/10.1016/j.apenergy.2018.02.024.

United Nations, 2015. Paris agreement under the united Nations framework convention on climate change (UNFCCC) [WWW Document]. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

Vargas-Salgado, C., Berna-Escriche, C., Escrivá-Castells, A., Alfonso-Solar, D., 2022. Optimization of the electricity generation mix using economic criteria with zero-emissions for stand-alone systems: case applied to Grand Canary Island in Spain. Prog. Nucl. Energy 151, 104329. https://doi.org/10.1016/j.pnucene.2022.104329.

Wang, Y.-H., Walter, R.K., White, C., Kehrli, M.D., Hamilton, S.F., Soper, P.H., Ruttenberg, B.I., 2019. Spatial and temporal variation of offshore wind power and its value along the Central California Coast. Environ. Res. Commun. 1, 121001 https://doi.org/10.1088/2515-7620/ab4ee1.

Zheng, C., Li, C., Gao, C., Liu, M., 2017. A seasonal grade division of the global offshore wind energy resource. Acta Oceanol. Sin. 36, 109–114. https://doi.org/10.1007/s13131-017-1043-x.