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Optimization of the electricity generation mix using economic criteria with zero-emissions for stand-alone systems: case applied to Grand Canary Island in Spain

Carlos Vargas-Salgado*, César Berna-Escriche, Alberto Escrivá-Castells, David Alfonso-Solar

Instituto Universitario de Ingeniería Energética, Universitat Politècnica de València (UPV), Camino de Vera 14, 46022 Valencia (Spain), Tel: +34 963879245

ABSTRACT

The extensive use of greenhouse gas-free energy sources is essential to achieve net zero emissions targets in electricity generation by mid-century; if such sources also increase the economic competitiveness by producing cheaper energy, the outlook is even better. With this purpose, the current study presents the combined use of the NuScale design, a promising type of small modular reactor (SMR), along with renewable sources and storage technologies. The widespread use of highly variable generation sources, such as wind and solar PV, poses significant challenges in trying to match electricity generation and demand. Therefore, more reliable generation sources and/or storage technologies combined with these highly volatile sources are necessary to meet the demand with guarantees and affordable costs. This issue is even more pronounced in isolated regions, such as islands, where at least one more reliable generation source and/or substantial energy storage capacity is required. The system, in many cases, is autonomous and needs to be 100% self-sufficient. Furthermore, to achieve the future goal of zero greenhouse gas emissions, it is necessary to eliminate fossil fuels in all areas, particularly in power generation, which significantly contributes to the total greenhouse gas emissions. Therefore, developing techniques to assess the feasibility of the combined use of different carbon-free technologies is required. Using renewable energies with nuclear energy coupled with storage technologies is a very good possibility to achieve these objectives. It was, in all likelihood, the best option in the case of isolated locations where the system must be self-sufficient precisely because of its isolation. The use of nuclear energy is a key part of the analysis if there is no reliable energy capable of covering approximately the off-peak demand, the rest of the systems will have to be greatly oversized, i.e., the power to be installed from renewables and/or storage will be unaffordable. Therefore, it is very useful to study these problems, especially in the case of islands. Specifically, this analysis has been applied to the Island of Grand Canary in Spain. This island has about 1,500 km^2 and nearly one million inhabitants, with a off-peak electricity demand of about 250 MW and a peak demand value of about 500 MW. The software HOMER was used to analyze and compare different alternatives, estimating the best combination to get the lower Levelized Cost Of Energy (LCOE). The system's total initial investment cost is 1,968 M€, the LCOE is 7.8 c€/kWh (25 years), and the payback is around 6.4 years.

Keywords: Stand-alone electricity generation, zero-emissions, economic competitiveness, renewable energy, small modular reactor, storage technologies, mathematical optimization modelling.

1. INTRODUCTION

The world's primary energy demand has been continuously growing during the last decades [1], even though this tendency has been partially interrupted by COVID-19 pandemic. A high percentage of this primary energy generation, around 80%, is covered by fossil fuels [2]; This scenario entails a double problem: the foreseeable depletion of fossil fuels, which would shortly endanger the electricity supply's continuity [3]**.** And a second problem, even more serious and in the shorter term, is the unacceptable growth of greenhouse gas emissions due to the use of these fossil fuels [4,5].

Currently, electricity generation is based on fossil fuels, approximately two-thirds of which are produced from fossil fuels. This makes it responsible for about 35% of the total CO_2 emissions of the energy sector [6]. This situation is even more pronounced on many islands, mainly due to their small size and isolated location. Since it is not possible to connect to a large grid, then in order to achieve the high reliability required for power generation, reliable sources must be used. Then fossil fuel generation sources, such as diesel, coal and gas, must then be used, leading to high greenhouse gas emissions. Therefore, electricity generation through cleaner technologies could contribute to achieving a zero-carbon scenario, becoming an important element for a sustainable energy system [7,8]. On the other hand, due to the unreliability and generation-demand decoupling of renewable energy systems, especially in the case of wind and photovoltaic [9–11], their combined use with other carbon-free sources such as nuclear should be considered to provide a necessary base of reliable energy that covers an important part of the off-peak periods [12–14]. Then with the use of renewable energies combined with nuclear not only the environmental aspects are considered but fossil fuel depletion and supply chain stability. On the one hand, the medium/long-term possibility of fossil fuels depletion and consequent increase in their price is prevented. On the other hand, and no less important, the elimination of a strong dependence on a supply chain that in many cases is based in countries with little stability, with the consequent risk of shortages or even shortages in the system. Both aspects lead, if not always to lower energy prices, at least to greater price stability, since the sources of cost uncertainty mentioned above are eliminated.

Moreover, in the case of large-scale use of these renewables, it becomes essential to have a base-relaible source and store the inevitable excess of electricity produced under certain conditions due to the existing decoupling between demand and production [15–18]. This use at a large scale could also lead to a problem in the islands' case because a huge number of locations would be needed, which might not be available [19]. Therefore, it is possible to obtain a reliable system combining renewables with consistent sources like nuclear and adding a storage set.

This paper proposes an optimized Zero-emissions stand-alone power generation system based on renewable energies supported by nuclear attending economic criteria for Grand Canary Island in Spain. The system includes wind, photovoltaic and nuclear sources. Also, a storage system is added to store energy when there are surpluses, allowing store energy from the nuclear plant to make the nuclear plant works close to its rated power.

Most Generation III reactors seem to be economically competitive with the rest of base-load electricity sources (i.e., gas and coal). But due to its size, most of the new designs of nuclear power units do not fit their electric necessities in off-grid areas. A nuclear plant has a very high electricity generation capacity, ranging from 1 to 1.6 GWe [20], exceeding by large the necessities of the majority of isolated areas. Nevertheless, many new designs with lower power ratings are being developed in the last few years; such designs are called small modular reactors (SMRs). Around 70 different concepts are currently being studied [21], 25 of which are evolutions of existent pressurized water reactors (PWRs). Many of them are high-temperature gas-cooled reactors (HTGRs), fast neutron spectrum, and molten salt designs. Most of the PWRs designs of SMRs consist of integrated reactors, which means that the pressurizer, steam generator, nuclear core, and, in many designs, recirculation pumps are enveloped, i.e., all the primary circuit is sealed with the pressure vessel.

Since NuScale [22] design is in an advanced state, this SMR has been chosen for the current study. In 2020, it received the US NRC licensing approval, which means that customers can develop projects base on NuScale power plants. The company plans to deliver the first NuScale modules to a customer in 2027. The first module is planned to be ongoing in 2029. The reference plant of NuScale 12-Module (12 NuScale reactors coupled) is scheduled to be fully operational in 2030 as part of the Utah Associated Municipal Power Systems (UAMPS) Carbon-Free Power Project (CFPP).

Wrigley's study [23] summarizes the studies carried out to evaluate the economic viability of SMRs against large reactors. Their reduced and compact size can balance out the disadvantages caused by the loss of economies of scale due to the reduced size of the SMRs, economies of learning and mass production, reduction in risks and finance, chain production instead of stick building, and reduced construction time, being as cheap as the novel large reactor designs [24–26]. The unique benefits that SMRs provide are mainly determined by the modularization (the whole reactor are constituted by several parts which are fabricated in modules in one or more factories, which allows transportation and on-site installation) and the modularity (different plant sizes can be built by the assembly of identical reactors of smaller capacity).

On the other hand, renewable power systems are mature technologies that should allow progressive substitution of conventional fossil technologies [27,28] however, the feasibility of this substitution is not so attractive due to economics and reliability concerns. Possible solutions to face these feasibility concerns can be based on combining different renewable sources (hybrid systems) and energy storage systems.

Aligned with the described above, decarbonization of the economy must be a reality by 2050 in the European Union countries; its members must move towards climate neutrality with 100% renewable consumption. In this way, the Canary Islands are working against the clock on their strategy to reduce their dependence on fossil fuels and their cost, taking profit from the abundant natural resources in the archipelago, such as the sun and the wind. The Instituto Tecnológico de Canarias (ITC), in charge of elaborating the studies to achieve the full decarbonization level, has contemplated up to ten scenarios to optimize clean and reach 100%. In all the scenarios, large-scale storage technologies would be necessary to achieve the objectives, particularly for Grand Canary Island; in fact, one hydroelectric power plant is proposed, the Chira-Soria project [29]. The Chira-Soria pumped storage plant would have a storage capacity of between 3.2 and 3.6 GWh, with a total generation power of 200 MW. Although, there is a strong local movement against this project since, for the Platform Save Chira-Soria, the project does not fit with sustainable development objectives, neither from social or ecological aspects, because it represents the expulsion of inhabitants and affects a protected area. Therefore, this study explores the feasibility of using mega batteries as a storage system.

The Hybrid Optimization Model for Multiple Energy Resources (HOMER) was used to analyze and compare the system. The software was developed by National Renewable Energy Laboratory (NREL) [30]. The software estimates the best size of a system, the investment, the LCOE, and the payback based on different energy sources. It is widely used by the scientific community to predict energy production and to choose the best option in both stand-alone and grid-tied systems [22], for planning installation of hybrid energy systems [26,31], to estimate its feasibility [32,33] and for integrating non-conventional source into a grid such as biomass gasification [34–37]. HOMER also can integrate storage systems [38], in HOMER, an off-grid system for a rural community in India integrating biomass, PV, and batteries, Suresh *et al.* [39] model in HOMER a hybrid system in India (PV, fuel cells, wind power, battery systems, biogas, and biomass). Chambon *et al.* provide an analysis of a hybrid system (biomass gasification and PV) in HOMER [40]. Alfonso-Solar *et al.* model a hybrid PV-biomass system for higher education buildings in HOMER [41].

To end this section by highlighting that this paper addresses the challenge of a zero-emission power generation applied to islands, where the proposed system must be autonomous since islands are usually not connected to an external grid. This paper provides novel solutions to address this problem, specifically the analysis of the combined use of new generation reactors (SMRs) and renewable energies and storage technologies, particularly mega-batteries. The final result will be an isolated system with an economically competitive generation mix and zero emissions.

To achieve the goals mentioned above, the methodology followed has been described in section 2. To contextualize the problem, the current generation system of the island has been described in section 3. Next, in section 4, the characteristics and information of all systems needed to carry out the simulations have been described. Section 5 describes the major results of the performed simulations. While section 6 is devoted to the discussion and conclusions of the current study regarding the needs of the generation system.

2. METHODOLOGY

The methodology consists of obtaining, from trusted sources, the input data for carrying out the simulations. The scheme of the method is shown in Figure 1. Among the inputs required to carry out the simulations, it could be mentioned: on year data of the hourly energy demand to be covered, technical information and cost of the generation system to consider (in this case PV, wind, and nuclear plants). If a storage system is required, it would be necessary information about its characteristics and cost. On the other hand, another required input is the energy resource of every power system (the solar and wind resources available in Grand Canary Island and information about Uranium used as a fuel in the nuclear plant). Other information necessary for simulations is financial information (such as annual interest rate and the project lifetime) and temperature (Mainly used to estimate the temperature losses in the PV system).

Using the previous information as an input in the Software HOMER, the best generation system combination options can be estimated to supply all the energy required (rated power and power generation of every system and storage needed capacity). In this case, always meeting the desired level of demand coverage, since the generation system is isolated from other grids, all the scenarios analyzed have 100% demand coverage. As a result, the best energy source combinations are obtained. Also, financial information such as the LCOE, initial capital, NPC, payback, and internal rate of return (IRR) are outputs of the simulation.

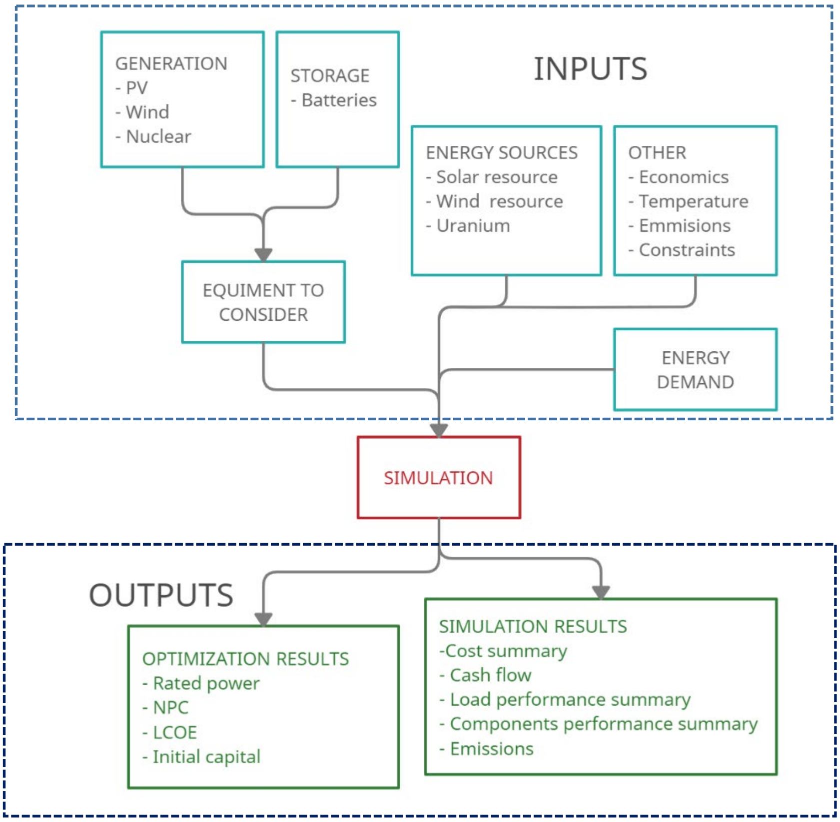

Figure 1 Schematic overview of inputs and outputs of HOMER Software.

2.1. Economic analysis

The estimated economic indicators are the Total Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Internal Rate of Return (IRR), and Payback (PB) [30,42,43].

- **Total NPC (C_{NPC}):** The total net present cost of a system is the present value of all the costs that it incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include residual value and grid sales revenue. The total net present cost uses the following equation :

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)}$$

Where *i* is the real interest rate and R_{proj} is the project lifetime in years (25 years for the present work).

- The Total Annualized cost ($C_{ann,tot}$) is the sum of the annualized costs of each system component, plus the other annualized cost. The annualized cost of a component is equal to its annual operating cost plus its capital and replacement costs annualized over the project lifetime.

  The capital recovery factor (CRF) is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the capital recovery factor is:

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

  Where *i* is the real interest rate (2% for the present work) and *N* is the number of years.

- **Levelized Cost of Energy (LCOE)**: It is the average cost per kWh of the electrical energy produced by the system. LCOE is calculated by dividing the annualized cost of producing electricity by the total useful electric energy production ($E_{useful.elect}$). The equation for the LCOE is as follows:

  $$LCOE = \frac{C_{ann,tot}}{E_{useful,elect}}$$

- **Internal rate of return (IRR):** It is the discount rate at which the grid and chosen PV system have the same net present cost. The IRR is calculated by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero.
- **Payback (PB):** Payback is the number of years at which the cumulative cash flow of the difference between the current and base case systems switches from negative to positive. It is calculated by dividing the difference in capital costs between the chosen system and the grid by the difference in operating costs. Payback indicates how many years it will take to recover an investment.

3. POWER GENERATION SYSTEM IN GRAND CANARY ISLAND

3.1. Energy demand

The demand for the Grand Canary Island in 2019 was 3.41 TWh/year. But when consulting the available historical data of the island [44], it can be seen that it presents stable demand values in the nine years analyzed. This indicates that the energy demand of the island is very stable. Despite in 2020, the pandemic of Covid-19 caused a drop in the energy demand; it is expected to return to its stable values over the next few years. However not only does this more or less stable electric demand data exist, but there are also two documents of the own Canary Islands government focused on their future energy forecasts. On the one hand, the document “Estrategia de Almacenamiento Energético de Canarias” [45] says that considering a BAU scenario, the growth of the population of the island (over 1 million inhabitants in the next decades) together with the growth of the GDP (around 2% per year) would lead to an increase in energy needs. But if collective mobility and energy efficiency policies are added to these considerations, the end result would be a reduction to about 2 TWh per year by mid-century. However, taking into account the document "Estrategia del vehículo eléctrico” [46], with the full implementation of the electric vehicle in the Grand Canary Island, it would lead to an increase of about 2.2 TWh of annual electricity consumption. But this forecast of total electrification of the economy is ambitious and will probably be difficult to achieve. Therefore, considering a less ambitious scenario, with around 50% penetration of the electric vehicle and considering the electrification of the rest of the electrifiable applications (industry, domestic economy, public services, etc.), it would lead to electricity demand values similar to those of 2019. For these reasons, the data for that year have been used to make the calculations presented in the current document.

Consequently, the demand data used for the calculations have been those of 2019. In particular, the 3.41 TWh/year of total energy demand, along with its maximum and minimum power (average in an hour), were approximately 550 and 250 MW, respectively. Figure 2 shows the daily average power demand curve. The daily average energy demand is 9.34 GWh.

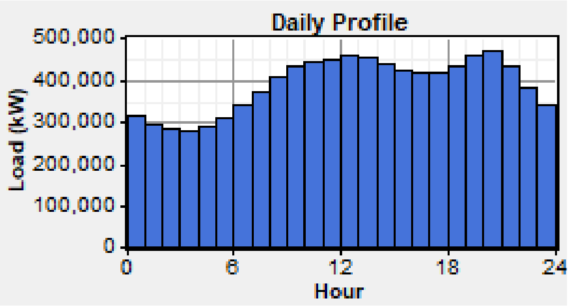

Figure 2. Average daily energy demand in Grand Canary Island – 2019.

3.2. Capacity

The information of the currently installed capacity of the Grand Canary Island has been obtained from the different energy yearbooks of the Canary Islands ("Anuario Energético de Canarias" yearbooks from 2011 to 2019, [44]). Figure 3 shows the summary of the installed power evolution in MW between 2011 and 2019. Figure 3 not only display the total installed power but also the major contributions of the different energy sources present on the Grand Canary Island, as well as the total sum of renewable and non-renewable energy sources. Highlight that the total installed power has been almost constant for these nine years. Figure 3 shows that all major contributions come from fossil fuel sources, specifically combined cycle, vapor turbine, gas turbine, and diesel. Although there is a slight upward slope in the installed capacity of renewable energies, this is not enough to reach the ambitious objective of zero emissions.

Focusing on the year 2019, only slightly less than 200 MW of the almost 1,200 MW of total installed capacity are wind and solar photovoltaic, with approximately 160 and 40 MW, respectively. In contrast, the installed power of generation technologies that use fossil fuels represents a very important part, more than 1,000 MW in total. Around 500 MW are combined cycle, almost 300 of steam turbine, about 200 of gas turbine and practically 100 of diesel. Speaking in percentages, only slightly more than 16% of the total installed power is renewable.

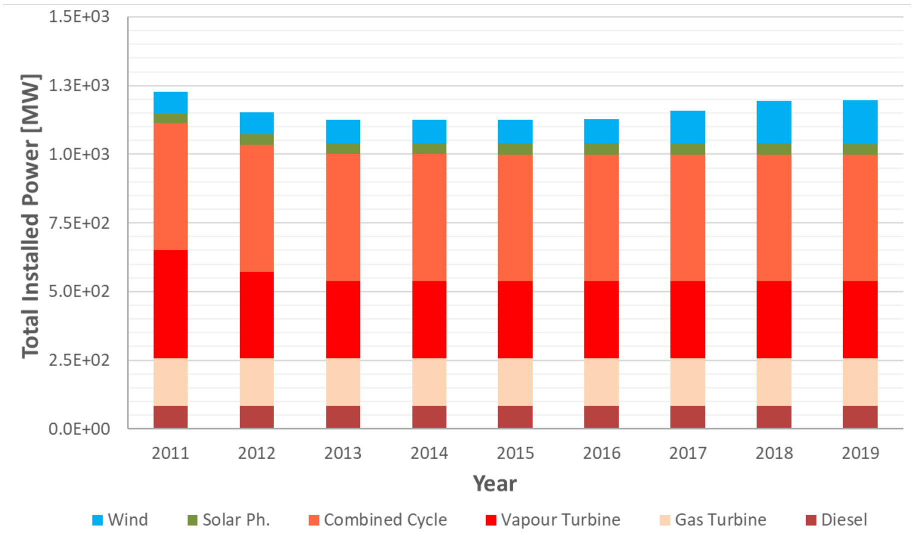

Figure 3. Bar chart of the installed power evolution between 2011 and 2019.

3.3. Energy generation by source

As for the total installed power, the information for the energy generation by sources has been obtained from the different energy yearbooks of the Canary Islands (“Anuario Energético de Canarias” yearbooks from 2011 to 2019, [44]). Figure 4 summarizes the energy generation evolution in GWh between 2011 and 2019 and installed power.

The same comments already made for installed power should be noted, i.e., the greatest weight in electricity generation falls on non-renewable energies. However, there has also been a slight increase in generation through renewable energies in recent years, especially due to wind power (Figure 4). It is also important to highlight an important aspect: the generation of energy is very stable. Therefore, based on these data, it is considered that its future variation will be reduced. Taking the current data, it can adequately estimate the future energy needs for the Grand Canary Island.

Focusing on the year 2019, in Figure 4 can be seen that combined cycle and vapor turbine produce more than 80% of the electricity generation. Only slightly less than 15% comes from renewable sources.

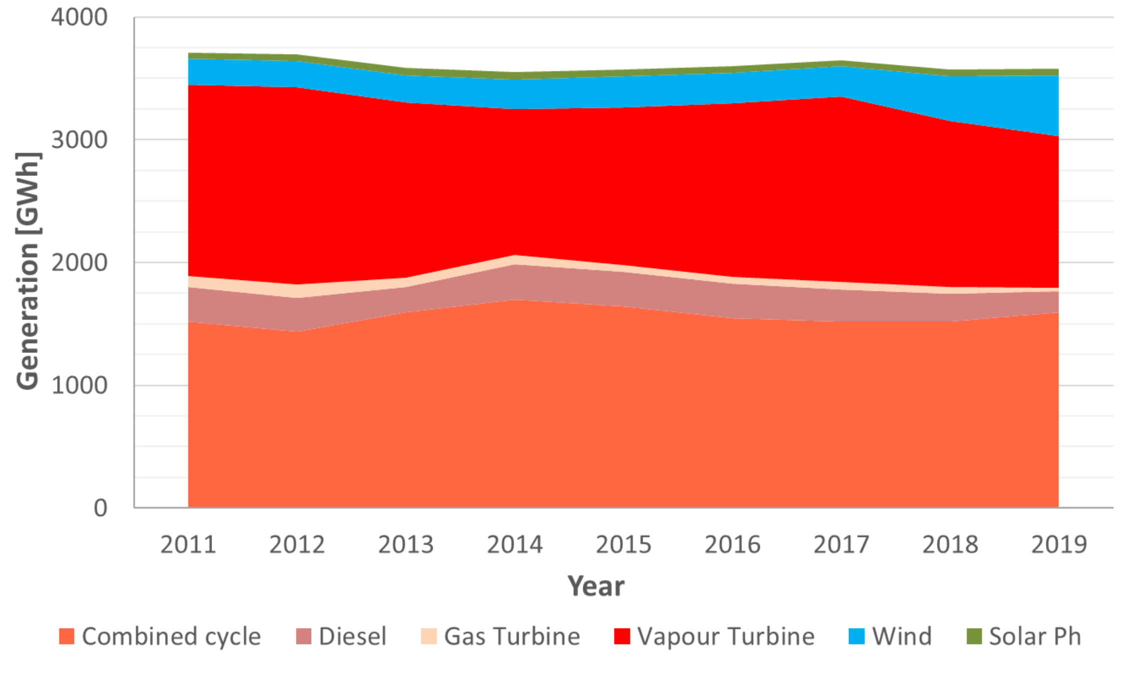

Figure 4 Evolution of the electricity generation by source in Grand Canary Island between 2011 and 2019.

4. SIMULATIONS INPUTS

As already mentioned in the previous section, the study “Estrategia del vehículo eléctrico de Canarias” [46] with full penetration of the electric vehicle in the Grand Canary Island would produce an increase of about 2.2 TWh in the annual electricity consumption. Although the forecast of total electrification of the economy along with full penetration of the electric vehicle is considered ambitious and will probably be difficult to achieve. Therefore, a less ambitious scenario has been analyzed, in which a 50% penetration of the electric vehicle is considered, together with the electrification of the rest of the electrifiable activities (industry, homes, commerce, services, etc.). This scenario leads to an annual electricity consumption of around 3.5 TWh for the island, which would mean maintaining the last ten years' demand values. To cover this demand, while maintaining an electricity generation system with zero greenhouse gas emissions in its operation, an integrated system of solar PV, wind and nuclear generation has been considered. In addition, the necessary storage capacity has been considered through the use of mega-batteries, given the current inhabitants' rejection for environmental reasons of the installation of large pumping plants (large occupation of the land and invading protected areas).

Then summarizing, the analyzed sources are nuclear, PV and Eolic. In addition, a battery system is used to store the surplus energy generated by renewable energies. The system is designed to cover 100% of energy demanded by the Grand Canary Island and meet the criteria of zero emissions at the lowest price (LCOE). Figure 5 shows a schematic view of the analysed sources to cover the energy demand.

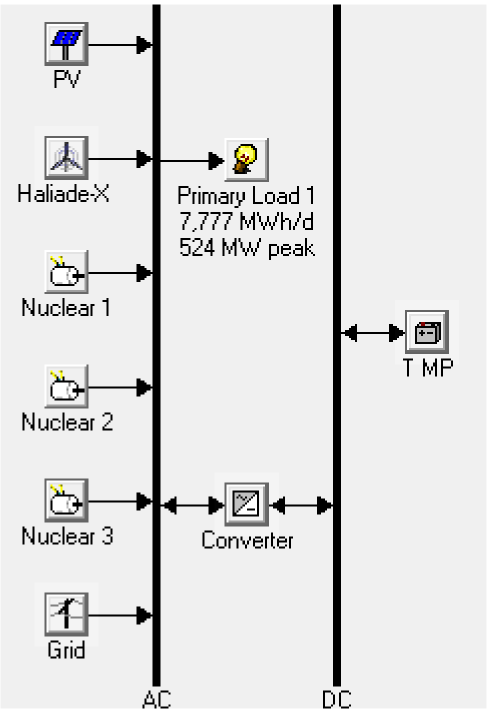

Figure 5. Scheme of the energy sources analysed.

4.1. Energy demand

The total energy demand of the island for 2019 was analyzed in section 3.1. In this year, the total energy demand was 3,410 GWh. Since one part of the island's energy demand is covered through a renewable system, this work aims to estimate the possibility of covering the total energy demand through a zero-emission system. This renewable energy has been subtracted to the energy demand to estimate the additional power to be installed to generate all the electric energy through zero-emission sources. Renewable systems available in 2019 produced 540 GWh covering 16.68% of the energy demand. To estimate the energy demand to be covered, hourly data of the total power demand were used, subtracting the hourly power produced by renewable energy systems (these data are obtained from the RRE webpage [56]). As a result, the remaining average daily power is obtained (Figure 6). Then, this energy produced by the current fossil system, around 2,800 – 2,900 GWh/yr, will have to be covered with renewable sources.

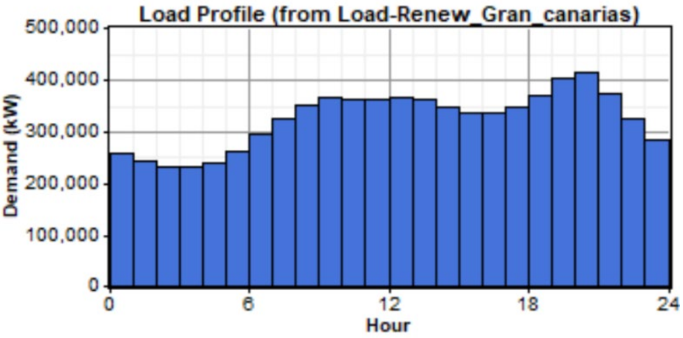

Figure 6. Mean daily energy produced by fossils systems in Grand Canary Island – 2019.

4.2. Nuclear Plant

Nuclear reactors become interesting since they have high reliability, zero emissions of polluting gases, and a very low generation price. This high reliability comes not only from its high capacity factor (close to 100%), but also from the very low supply needs for its operation (refueling every two years of 1/3 of the total core fuel, usually the plant has closed several contracts in advance, and even has part of the fresh fuel in its facilities).

Among the huge number of nuclear plant designs, the NuScale design has been used here. This design includes the reactor vessel, steam generators, pressurizer, and containment vessel in a package that eliminates reactor coolant pumps and large core piping [22,34], Figure 7. As an additional advantage, highlight that this compact design effectively eliminates large break loss of coolant accidents (LBLOCAs). The coolant is driven by natural circulation and other basic physics phenomena, which means the easiness of management. Each NuScale power module (NPM) has a generation power of 57 MWe (60 MWe nominal power minus 3 of internal consumptions). Up to 12 NPMs can be incrementally added, which means up to 685 MWe of net power. Each one has thirty-seven fuel elements of 17×17 PWR fuel assemblies with about 2 meters in length. One-third of the core is replaced each 24-months fuel cycle, which means that fuel remains six years in the core. An important feature is that the core can be cooled indefinitely with a three-stage cooling system, the Triple Crown safety system (the system that does not need an operator or computer action, ac/dc power, and/or additional water). The NuScale design incorporates seven layers of defense instead of the usual four barriers of a typical reactor, indicating an extremely high safety design.

Traditionally, all reactors are of large sizes regarding the monetary aspects because of the advantages of economies of scale. There have been many analyses on trying to estimate the economic viability of SMRs against large reactors. Ad summary can be found in Wrigley's study [23], or recently a NEA report [47], explores the challenges and opportunities of SMRs. The disadvantages caused by the loss of economies of scale due to the reduced size of the SMRs can be balanced out by their simplified design, reduced and compact size, economies of learning and mass production, reduction in risks and finance, standardization, and chain production instead of stick building, reduced construction time, etc., being at least as cheap as the novel large reactor designs [24,47–49]. In particular, the unique benefits that SMRs provide are mainly determined by the modularization (the whole reactor are constituted by several parts which are fabricated in modules in one or more factories, which allows transportation and on-site installation) and the modularity (different plant sizes can be built by the assembly of identical reactors of smaller capacity).

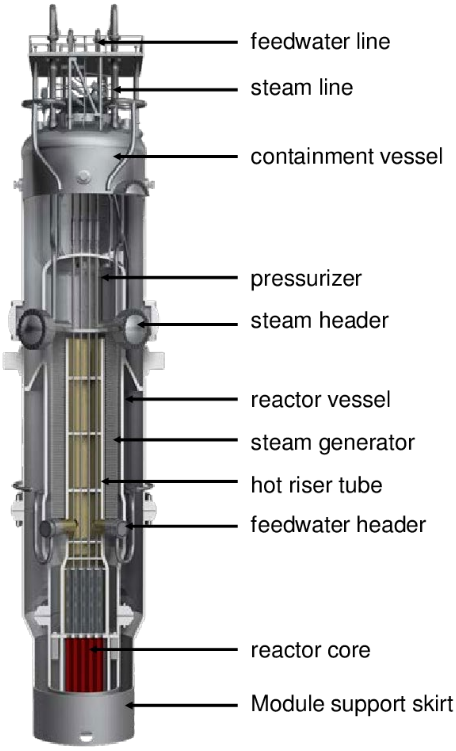

Figure 7. NuScale small modular reactor design [22].

For the NuScale reactor, the estimates carried out by the vendor indicate that its final construction costs are significantly lower than the calculations of other competitors, around 3,000 €/kW of installed power [22], against the approximately 4,250 €/kW, which is generally assumed as an average cost for an SMR capital costs [31,48]. In particular, on Mignaca and Locatelli [50], research suggests that these costs are slightly below 4000 €/kW for the NuScale design. The assumed operation and maintenance costs are around 12.3 €/MWh, while the fuel cost is about 8.2 €/MWh, typical values supposed for the SMRs designs [31] limited data of decommissioning costs are available. Still, values between 9 and 15% of the constructions costs are typical figures [51]. Finally, according to the Canadian joint waste owners, the spent fuel management would probably cost around 100 €/kg fuel bundle[51].

The capacity factor is the ratio between the plant's energy and the energy produced if the plant were working at nominal power for an entire year. Capacity factors around 90% are supposed for all the SMRs designs; in particular, the company states that capacity factors higher than 95% will be reached for the NuScale modules [22,23,48]. Aspects to consider for achieving a high capacity factor are refueling, unplanned shutdowns, planned maintenance, and load following. Of these contributions, unplanned shutdowns are the most difficult to manage, as they can occur at any time. However, due to NuScale's simpler design and smaller components than large reactors, there is less chance of component or system failures, so the NuScale vendors claim that 99.95% availability will be achieved in the electrical output to the grid. These figures mean that, on average, there will be less than 5 hours per year of outages due to these unscheduled failures; then, almost all shutdowns can be planned. Finally, the expected 15 for most of SMR designs, including the NuScale, reaches 60 years [22,23].

4.3. PV Solar System

Grand Canary Island is part of a Spanish archipelago located on the Atlantic coast (Latitude: 28° 05' 59.03" N; Longitude: -15° 24' 48.35" W). The solar resource is estimated using the European photovoltaic geographical information system (PVGIS). The Monthly solar energy resource in Grand Canary is shown in Figure 8. The potential global horizontal irradiance is about 2,130 ESH/year (ESH = Equivalent sun hours). If the panels face the south and the used angle is optimal (24 to 26°), the potential increases to 2,300 ESH/year. Basic inputs of the PV system are shown in Table 1, along with the datasheet of the panel, which are shown in

Table 2.

Table 1 Inputs used for the PV system.

Lifetime (years)	25
Derating factor (%)	85
Panel tilt angle	25°

Table 2 Inputs used for the PV system [52,53]**.**

Used panel	**Trina solar TSM-DE19**
Temperature coefficient of power (%/°C)	-0.36
Peak Power (W)	550
Nominal operating cell temperature (°C)	42.6
Efficiency of the panel at standard conditions (%)	20.5
Cost of the entire PV system (k€/MW)	800
O&M cost (per 1MW peak power) (€/year)	35,000

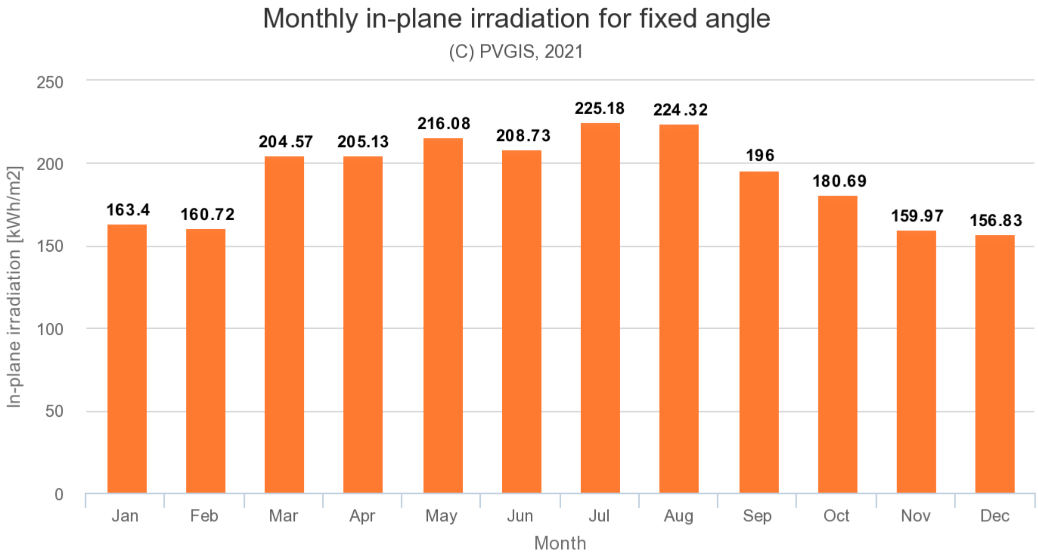

Figure 8. Monthly In-plane irradiation for 25° angle - Grand Canary [54].

4.4. Wind system

As for the solar resource, wind resource has been estimated for the particular site of the Grand Canary Island. Due to its potential, the current platform wind systems technologies off-shores wind energy systems will be analyzed. The average distance to the coastline has not stopped growing over the last ten years. European off-shore wind farms were an average of just over ten kilometers from the coast in 2010; 20 kilometers on average in 2013; more than 30 kilometers in 2016; 40 kilometers in 2018; and 59, on average, in 2019. The same thing has happened with the waters, less than 15 meters of average depth in 2011, more than 20 in 2015, and well over 30 in 2019 [65, 66]. And now, in addition, there are floating designs, this solution allows wind farms to be located without the restriction of shallow waters, so that winds are sought in any location. There are already projects in the United Kingdom, Portugal, Norway and France [56].

The wind resource is estimated using the global wind data of the second Modern-Era Retrospective analysis for Research and Applications (MERRA-2) developed by NASA [57]. The location of the off-shore wind generator would be from 2 to 5 km in the area with more potential according to from global wind atlas [58]. The wind energy resource in Grand Canary is shown in Figure 9; a favorable location to install the wind generator is the island's southeast. The monthly average wind velocity in this area is shown in Figure 10. Other required information for wind power simulation is taken from [57] and shown in Table 3, wpecifically, the datasheet of the selected wind generator is shown in

Table 4.

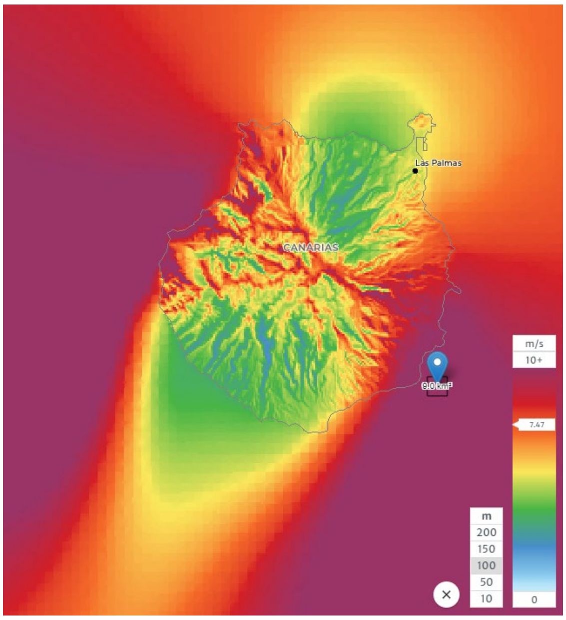

Figure 9. Off-shore Wind resource in Grand Canary [58].

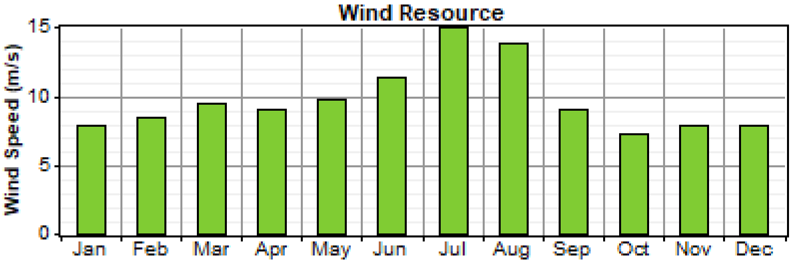

Figure 10. Monthly wind energy resource in Grand Canary [57].

Table 3 Inputs used for the simulation [57].

Weibull k	2.0
Altitude, m asl	0
Anemometer height (m)	50
Wind speed profile	Logarithmic
Surface roughness length (for Blown see) (m)	0.0005

Table 4 Datasheet of the wind turbine Haliade-X [52,57,59].

Wind generator	Haliade-X General Electric
Rated power (MW)	12
Rotor diameter (m)	220
Height to the axe (m)	140
Total height (m)	248
Cost of the system (M€/turbine)	28.6
Cost per power unit (M€/MW)	2.38
O&M cost (M€/year)	3.5

4.5. Storage system

A storage system is required to meet the energy demand and production, obtain an energy balance, and resolve the intermittency problem in renewable energy. The major information needed about the used storage system, mega-batteries Tesla Megapack, is summarized in Table 5.

Table 5 standard system specifications of the selected battery system [60–63]**.**

Battery	Tesla Megapack
Maximum AC power 2-hour (MW)	1.26
Energy Available per Megapack 2-hour (MWh)	2.53
Round-Trip System Efficiency	87%
Total heigh**t** (m)	220 m
Cost of the module (€)	760,000
O&M cost (€/year)	10,800

4.6. Cost of the energy

Since the energy cost for every source is not available for 2019, the cost used is the real hourly cost for all the Canarias islands. This cost includes the mix of renewable and non-renewable sources; it is a conservative value. The hourly energy cost is taken from the Spanish electricity system operator (ESIOS web page) [64], being respectively the maximum, average, and minimum values equal to 24.4, 15.3, and 10.4 c€/kWh.

5. RESULTS

The main results of part of the analyzed simulations are summarized in Table 6. The best option from the economic point of view is to install 150 MWp of PV, 25 wind generators (12 MW each, 300 MW in total), 3 SMRs (57 MW each one, 171 in total), and a storage system compound of 476 batteries (each battery can store 2.53 MWh, a total capacity of 1.2 GWh). The maximum power able to be delivered by the storage system is 600 MW. This means that total installed power of 621 MW plus batteries can deliver another additional 600 MWp of electricity capacity transfer. Despite the symbol for money showed in the graphs is $, all inputs values are given in €; consequently, the unit of the obtained value is €.

As also shown in Table 6 , the initial investment is 1,968 M€, the O&M costs are around 123.3 M€/year, and the LCOE is 7.8 c€/kWh (25 years). The renewable energy fraction is 58%, while the nuclear system produces 42% of the required energy, the total NPC cost is 4,375 M€. As a summary, Table 7 LCOE Analysis summary.provides a cost and generation percentage breakdowns of the different generation sources, their weighted average value, as well as the average cost of energy in the Canary Islands for the year

2019, in order to provide an idea of the cost savings that would result from the installation of the proposed system.

Table 6 Results of some of the analyzed combinations.

	PV	**Wind Turbines**	**Nuclear**	**Initial capital**	**O&M**	**NPC**	**COE**
Units	(MW)	(MW)	(MW)	(M€)	(M€/yr)	(M€)	(c€/kWh)
1	150	300	171	1,968	123	4,375	7.8
2	175	300	171	1,988	124	4,413	8.0
3	200	300	171	2,008	125	4,450	8.0
4	0	360	171	1,991	135	4,634	8.4
5	150	360	171	2,111	141	4,858	8.8
6	175	360	171	2,131	142	4,896	8.9
7	200	360	171	2,151	143	4,934	9.0
8	150	420	171	1,997	152	4,974	9.0

Table 7 LCOE Analysis summary.

Source	LCOE (c€/kWh)	Generation (%)
Solar PV	5.2	7.7%
Wind	8.5	50.7%
Nuclear	4.8	41.6%
Batteries	9.0	12.3%*
Avg. System	7.8	-
Excess Electricity	-	10.2%
Canary Islands, 2019	15.3	--

*This value is the percentage of energy that is stored into the batteries and used to fed the grid.

5.1. Economic analysis

The initial capital required to implement the system is 1,968 M€ of which, 6.1%, 36.3%, 39.2%, and 18.4% correspond to the PV, wind, nuclear, and batteries, respectively. In Table 8 it is included information about initial investment and all the costs during the lifetime of the project (considered as 25 year) . In Figure 11, the total NPC costs along the lifespan of the system are shown, the highest one is the wind with approximately 2,423 M€, followed by the SMRs with 1,110 M€, the batteries a 616 M€ and finally the solar PV with around 226 M€. Consequently, the O&M cost supposes 2,263 M€ during the system's lifespan, 75.5% of such cost goes to the wind system. A summary of the economic analysis is shown in

Table 9.

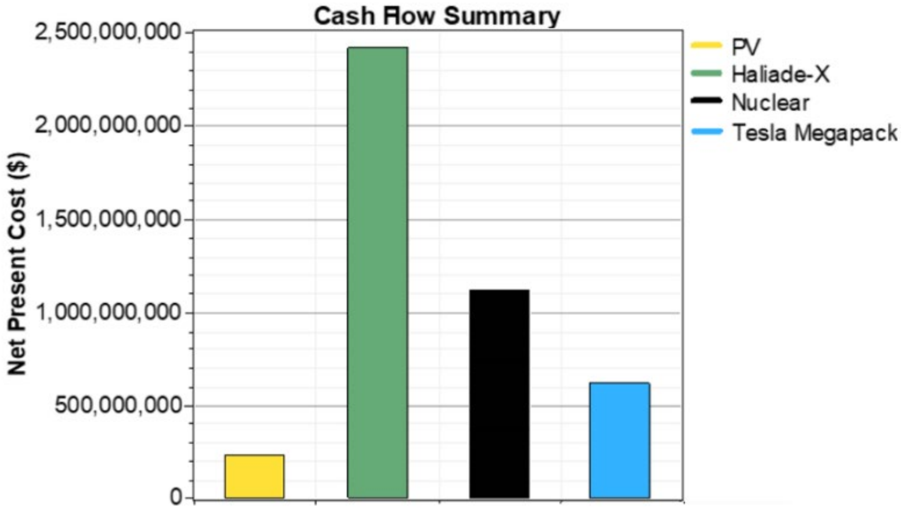

Figure 11. Initial investment per energy source.

Table 8 Initial capital, O&M cost, Fuel cost and Salvage. Total and per source.

Component	Capital (M€)	% Capital	Repla. (M€)	O&M (M€)	% O&M	Fuel (M€)	Salvage (M€)	Total (M€)
Solar PV	120	6.1%	0.0	105.7	4.7%	0.0	0.0	226
Wind	715	36.3%	0.0	1,708.3	75.5%	0.0	0.0	2,423
Nuclear	771	39.2%	0.0	348.6	5.1%	244	-253.6	1,110
Battery	362	18.4%	212.2	100.4	4.4%	0.0	-58.0	616
Whole system	1,968	100%	212	2,262.9	100%	244	-312	4,375

Table 9 Economic analysis summary.

Present worth (M€)	4,107
Annual worth (M€/yr)	210.4
Return on investment (%)	16.0%
Internal rate of return (%)	14.9%
Simple payback (yrs)	4.9

5.2. Energy balance

As shown in Figure 12, there is an equilibrated balance in the yearly energy production per source. It is widely recognized that nuclear reactors, and SMRs in particular, have a constant energy generation rate. But not only such source had this stability in the Grand Canary Island generation system developed in the current study. Wind power also has a monthly averaged generation rate quite constant due to the privileged location of the island in which wind is considerably high and quite stable, particularly for the off-shore generation, which has been selected for the analysis. Regarding solar PV generation, the island's location allows having a high number of sunshine hours added to high insolation, which leads to an elevated and quite constant average generation. Thus, with the help of a battery system, the final result is the high reliability of the system. In fact, it can operate autonomously to cover 100% of the energy demand.

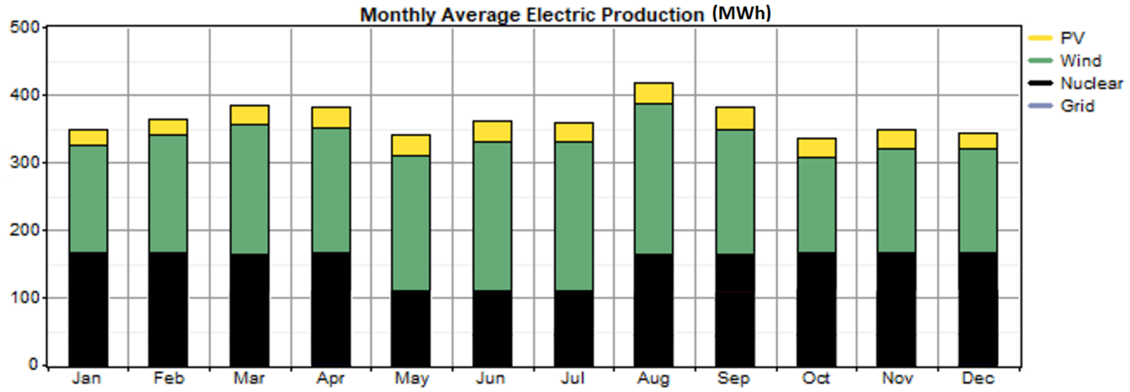

Figure 12. Monthly average electricity production per source (MWh).

Table 10 summarizes the percentages each energy source covers; as shown, almost 60% is covered by renewable sources (solar PV and wind), while the SMRs cover the remaining 42%. It should be noted that, mainly due to the high reliability of the nuclear generation and due to the high capacity of the batteries of the proposed design, there is a low excess of electricity generation (10.2%), even though this is an isolated system. Excess electricity is referred to electricity that must be dumped because it cannot be used to serve a load or charge batteries.Therefore, the current design provides great flexibility and adaptability between generation and demand.

Table 10 Energy demand and energy production per component.

Production	**GWh/yr**	**%**
PV array	247	7.7%
Wind turbines	1,619	50.7%
Nuclear	1,330	41.6%
Total	3,196	100%
AC energy demand	2,839	
Excess electricity	326.7	10.2%
Capacity shortage	0	0%

If generation systems and the storage system are separately analyzed, some significant aspects can be highlighted. The generation map of the solar PV system (Figure 13) shows a quite constant generation rate, widen during the summer months but with a considerable generation capacity during the whole year. The results are summarized in Table 11. As a result, an elevated average and total output values of generation are obtained, which leads to a reduced LCOE (5.2 c€/kWh). The map also shows, unlike what happens in the peninsula, the energy production in winter and summer is not significantly different. The reason is Canarias is located in a lower latitude.

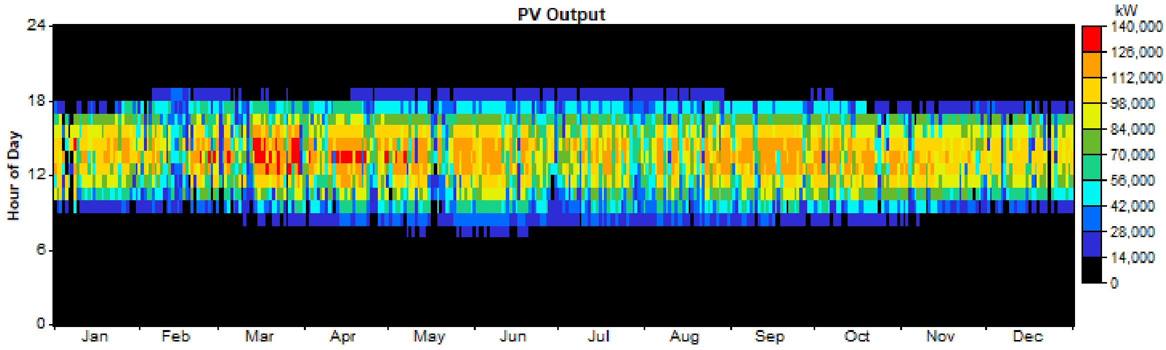

Figure 13. Generation map of the solar PV system.

Table 11 PV system summary.

Quantity	Value	Units
Rated capacity	150	MW
Mean output	28.1	MW
Mean output	675.4	MWh/d
Capacity factor	18.8	%
Total production	246.5	GWh/yr
PV penetration	8.7%	%
Hours of operation	4,121	hr/yr
LCOE	5.2	c€/kWh

Moving to the off-shore wind power system highlights that, as shown in the generation map (Figure 14). Because during the summer, the wind velocity is bigger compared to the rest of the year (Figure 10), the energy production is also bigger from June to August. The electricity generation is very high during the day and night, with electric generation figures close to the total installed power. Table 12 shows a value of more than 60% of the capacity factor for the wind system, which is extremely high and can only be achieved due to the privileged location of the island and the fact that windmills generate it at sea winds are even more constant. However, the generation cost is not very low, 8.5 €/kWh, mainly due to the high O&M costs of these off-shore systems.

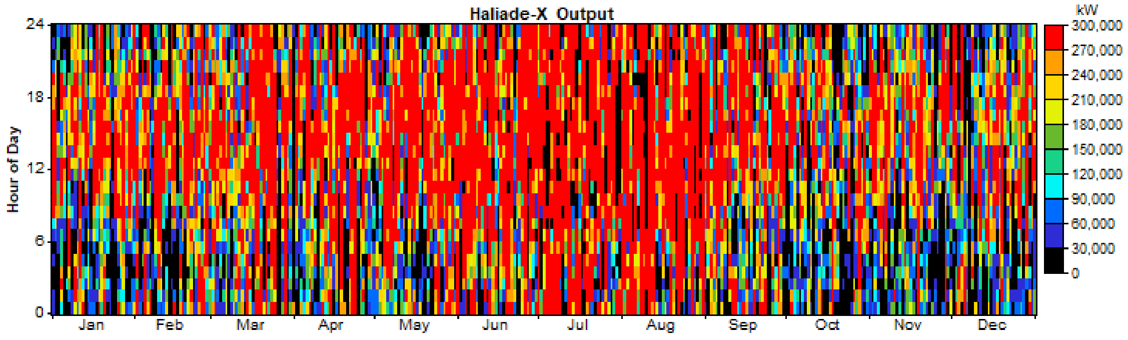

Figure 14. Wind system power production during one entire year.

Table 12 Wind system summary.

Quantity	Value	Units
Total rated capacity	300	MW
Mean output	185	MW
Capacity factor	61.6	%
Total production	1,619	GWh/yr
Wind penetration	57	%
Hours of operation	8,177	hr/yr
LCOE	8.5	c€/kWh

Concerning the SMR generation system (Table 13), all nuclear reactors have a constant and trustworthy generation rate. Due to their novelty, conservative capacity factors have been used for the current design, the NuScale vendors' state values above 95%. Still, the current study has been carried out with values below 90%. Despite this, generation from this source is very considerable. It can cover practically all of the island's consumption during off-peak demand periods and contribute significantly to the rest of the periods.

Table 13 Nuclear system summary.

Quantity	Nu1	Nu2	Nu3	Avg/Total	Units
Hours of operation	8,016	8,040	8,040	8,032	hr/yr
Capacity factor	88.6	88.9	88.9	88.8	%
Electrical production	442.6	443.8	442.9	1,329.2	GWh/yr
Rated power	57.0	57.0	57.0	171.0	MW
Fuel consumption	1,025	1,098	1,096	3,219	kg/yr
Fuel energy input	510	511	510	1,531	GWh/yr
Mean electrical efficiency	86.8	86.8	86.8	86.8	%
LCOE	4.8	4.8	4.8	4.8	c€/kWh

Finally, the mega battery storage system summary is presented in Table 14; this system has a total storage capacity of 1.22 GWh. The map for the state of the batteries charge (Figure 15) demonstrates their importance to maintain the figures of the total installed power of the renewable needed to cover the demand in acceptable values. Without it, an unaffordable installed power would have been required to meet the demand and, in addition, a huge amount of energy would have been wasted for many periods. Figure 16 shows that the batteries are between 20 and 100% of the charge most of the year. But there are almost all degrees of charge throughout the year, with considerable periods around 60% charge, even reaching quite deep discharges of around 10-15% for about 1-2% of the time. Instead, the battery system is fully charged almost 50% of the year; this system allows an increase in the system's reliability when intermittent renewables sources are used as a source.

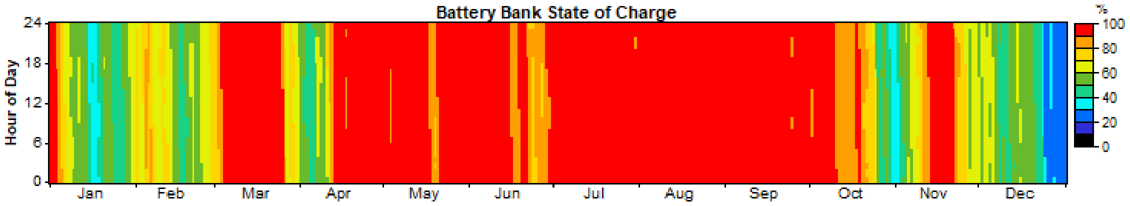

Figure 15 Storage system SoC during one entire year.

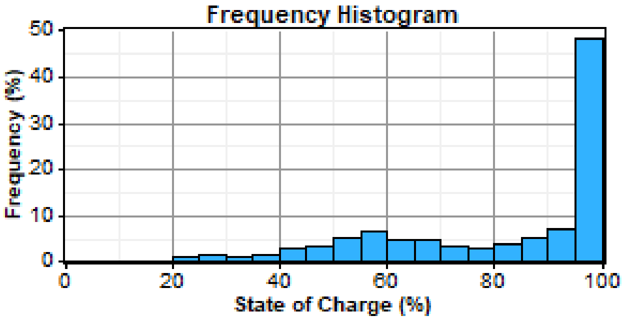

Figure 16 Frequency histogram of the storage system.

Table 14 Storage system summary.

Quantity	**Value**	**Units**
Batteries	476	
Bus voltage	505	V
Nominal capacity	1.22	GWh
Usable nominal capacity	1.22	GWh
Autonomy	3.75	hr
Lifetime throughput	141,551	GWh
Energy in	381.2	GWh/yr
Energy out	351.6	GWh/yr
Expected life	15	yr
LCOE	9	c€/kWh

6. CONCLUSIONS AND DISCUSSION

Reducing greenhouse gas emissions is a key aspect of the electricity generation-systems; along with this paper, a generation system based on zero-emission technologies is analyzed for the Grand Canary Island. The electricity generation sources are based on technologies that use fossil fuels have to be replaced; in the Grand Canary Island, it supposes more than 80% nowadays. In the case of islands, the elimination of these technologies provides another additional advantage, as most islands are isolated systems. It is important to be self-sufficient since the system has to provide the necessary energy under any situation. The dependency on fossil fuel technologies makes impossible this energetic independence because a continuous flux of fuel (oil, gas, carbon) has to be received by the island almost every day. This situation does not occur when renewable sources are used; wind and sun are always available (although these sources suffer from typical uncertainty/randomness). SMRs do not have this dependence either, since the fuel requirement is very low, and only 1/3 of the core fuel is planned to be replaced every two years; and in addition, the plant facilities can have stored the necessary fuel for a complete refueling.

Many alternatives have been simulated using HOMER code imposing the condition of fullfilling 100% of electricity demand with renewable and nuclear sources (so zero-emission). The input data required were the characteristics of wind, solar, nuclear, and battery equipment. In addition, estimates of the wind and solar resources available on the island have been used, together with demand estimates. NPC is calculated for every alternative and feasible solutions ar ordered according to this indicator, so lowest NPC alternative is the optimal one. This economic criterion is implicitly associated with a compromise solution with the necessary oversizing the renewable generation sources but with moderate both excess of electricity and expenditure in the storage system. So implementing this model for the Grand Canary Island has led to the conclusion that the best option is to install 150 MWp of solar PV, 300 MW of wind, 171 MW of nuclear, and a storage capacity of 1.2 GWh (600 MWp of electricity capacity transfer during 2 hours). Having reached a system with an oversizing of the sources reduced generation and batteries of an appreciable capacity, with only 10.2% of excess electricity (because it cannot be used to serve a load or charge the batteries as they are full of charge). Having a final figure of initial investment is 1,968 M€, and O&M costs around 123.3 M€/year and an LCOE of 7.8 c€/kWh (with 25 years of use), and the payback is around 6.4 years

The methodology used would be applied to any place, preferably to those isolated systems; it would only be necessary to make the corresponding modifications of the insolation conditions and wind maps and introduce the particular data of the demand. Grand Canary has about 1,500 km^2 and a population slightly below 1 million inhabitants and has privileged conditions of light and wind, which makes it very suitable for implementing renewable energies. The capacity factors of renewable technologies are very high.

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