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Second-life electric vehicle batteries as a wind energy storage system to avoid power reductions. A case study in Tenerife, Spain.

Author:	Aaron Isaac López Tacoronte
Master's degree:	Renewable Energy
Advisor:	Juan Albino Méndez Pérez
Department:	Computer Science and Systems Engineering

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Abstract

Increasing energy demand leads to environmental challenges such as global warming and climate change. This situation requires a paradigm shift to take place in the ways of generating energy. Sustainable carbon-free energy sources, such as wind or solar, must increase rapidly to replace the generation systems based on conventional sources that predominate today. However, the increase in the use of renewable energy systems has produced an instability of the grid, due to the stochastic nature of this type of energy, especially wind energy. These challenges require storage systems that provide viable power system operation solutions.

In this work, the use of second-life electric vehicle batteries has been proposed to design electrical energy storage systems at a lower cost, so that surplus wind energy can be stored at times of low electricity demand and high wind resources, and thus, being able to avoid power reductions, with the main objective of reducing energy waste and making intelligent use of stored energy, in order to obtain an additional economic benefit. Firstly, the role of wind energy in the electricity generation structure of the island of Tenerife, Spain, has been studied. Second, research has been carried out on electric mobility on the island under study, so that the capacity of second-life electric vehicle batteries that may be available in the future can be estimated. And, finally, a technical and economic feasibility study has been carried out for the introduction of these storage systems in a wind farm in Tenerife. In the future, the proposed technology has the potential to become a low-cost battery energy storage system that is essential for increasing the integration of renewable energy into the grid, as well as reducing the environmental footprint by prolonging the useful life of the batteries for electric vehicles, which will offer added value to the entire system.

Keywords: Isolated electrical systems, renewable energies integration, wind energy, energy storage systems, second-life electric vehicle batteries.

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1. Introduction

Currently, a paradigm shift is taking place in power generation technologies, which has resulted in the replacement of generation systems based on conventional sources with renewable generation systems. However, the increase in the use of renewable energy sources has produced an instability of the grid due to the non-dispatchable nature of this type of energy, especially wind energy [1]. It is known that large wind energy penetrations are avoided in most modern energy systems, due to its highly stochastic nature. An important aspect of this uncertainty is the large power gradients that wind farms can impose on the grid, affecting both the overall optimization and stability of the system, as well as the quality of the energy generated by it [2].

Frequency regulation has become one of the most crucial challenges of the modern electrical system due to the decrease in inertia [3]. However, fast-response energy storage technologies (batteries, supercapacitors, flywheels and superconducting magnetic energy storage) are recognized as viable sources to provide frequency regulation in the power system with high penetration of renewable energy, thus improving operational reliability and efficiency in energy use [3][4]. Specifically, the introduction of battery energy storage systems in wind farms allows them to function as conventional power plants that promote the integration of wind energy in the electricity grid, and in turn, generate energy security, substantial cost savings and a reduction of greenhouse gas emissions, which will make it possible to meet the emission targets established by Europe.

Fluctuations added to the already variable nature of frequency deviation and decreased frequency stability by reducing inertia and dimming ability due to intermittent characteristics of the frequency are discussed in depth in [5]. Another more recent article [6] analyses the load frequency control of a hybrid system, made up of thermal and hydroelectric power plants in presence of non-programmed wind plants, in different operating modes and at various penetration levels.

In order to mitigate fluctuations and the variable availability of wind energy and to allow a greater penetration of this type of energy in the grid, various solutions have been investigated and proposed. Some interesting proposals will be mentioned below. In [7] a method of co-optimization of an offshore wind farm with a battery energy storage system is proposed, which allows the wind farm to participate in the electricity market two days ahead and the reserve market of primary frequency control. [8] presents a novel energy management system that can minimize the daily operating cost of a micro-grid and maximize the self-consumption of renewable energy by determining the best configuration for a central battery energy storage system based on a defined cost function. In [9] a novel approach is proposed, where predictive control is used to regulate the state of charge of a hybrid energy storage system in variable scenarios.

It is well known that electrical energy storage technologies have great potential to meet the transmission and distribution challenges present in the grid. However, the wide variety of options and complex characteristic matrices make it difficult to evaluate a specific technology for a particular application. A complete and clear picture of available state-of-the-art technologies and where they would be suitable for integration into a power generation and distribution system is provided in [10]. This other paper [3] comprehensively reviews the applications of fast response storage technologies most effectively for frequency regulation services. As an example of the application of storage systems for a greater penetration of renewable energies in the grid, [6] proposes a battery charging mode, in which discharged batteries are transported from battery exchange stations in areas of high load to wind farms, to alleviate the power reduction.

However, despite the benefits of using energy storage systems, the high cost of batteries keeps investors away. Fortunately, the batteries removed from electric vehicles still have sufficient capacity to be reused and could be obtained cheaply [11]. The reuse of batteries removed from electric vehicles in renewable energy systems is a relatively new concept [12][13]. Second-life batteries are defined as those that are removed from electric vehicles when their energy density has degraded below the level required for motor applications, but are still efficient enough for less demanding stationary applications. This proposal is beginning to attract the attention of major original equipment manufacturers such as Nissan-Renault, BMW, Tesla or Daimler [14][15]. In the future, it could become an abundant and environmentally benign source of low-cost energy storage system [16].

Electric vehicles are considered one of the most promising solutions for the de-carbonization of transport sector, and lithium-ion batteries are one of key technologies to enable the techno-economic viability of mass-adopted electric vehicles [13][14]. In fact, the governments of many countries are providing strong support to encourage the development of these vehicles, receiving the highest priority on the sustainable development agenda [17][18]. The arrival of the electric vehicle is more and more a reality, and in the coming years its use will spread to dominate the automotive market. Although its implementation will be a revolution from the environmental point of view, there are still certain aspects that must be reviewed so that the technology is completely sustainable. A key element is batteries and their environmental impact. Despite of the delay in the development of the charging infrastructure and the anxiety about the reach of potential customers, the current projections of the absorption of electric vehicles indicate that, globally, several gigawatt hours of used batteries are likely to be withdrawn from these types of vehicles annually by 2030. The challenge this poses for recycling facilities is immense [16].

Electric vehicles demand high performance from their batteries, so once the battery capacity drops to 70–80%, it must be replaced with a new one. During that point, the batteries can still handle a good amount of charge and discharge and thus there is a second battery life that can be deployed in other less demanding applications, where the limits of performance, volume and weight of it are not critical. For example, static energy storage applications such as grid storage, renewable power plants, ancillary services market, residential use, etc. This use of the battery for secondary applications will help delay the process of recycling the battery or disposing of the ingenious product used in the battery, as well as reducing the cost of electric vehicles and storage for stationary applications [13][16][18]. In [19] the environmental trade-offs of the cascade reuse of lithium-ion electric vehicles batteries in stationary energy storage have been analysed. Another study [20] has focused on the introduction of industrial battery energy storage systems built from lithium batteries removed from electric vehicles with different health states. In [16] a methodology has been developed to predict second-life battery price and sales quantities up to 2050.

On the other hand, the degradation behaviour of second-life batteries remains unknown and represents one of the biggest gaps in the literature. [13] has evaluated the effects of lithium-ion nickel, manganese, cobalt/carbon battery health status and second-life aging history in two different applications: a residential demand management application and a renewable integration application using power smoothing. [21] developed an effective health indicator to indicate the health status of the lithium-ion battery and a method based on moving windows to predict the remaining life of the battery. Other recent investigation [17] has studied the optimal choice of strategies for the allocation of battery capacity by an electric vehicle manufacturer in the presence of battery recycling.

Despite the fact that the proposed technology has not yet reached an acceptable level of maturity that guarantees its profitability and reliability, some projects can be found that have started to make use of it. For example, Nissan's ground-breaking project to reuse its electric car batteries for public lighting in Fukushima [22]. Furthermore, in [12] a hybrid energy system composed of a photovoltaic system, hydrogen technology and second-life electric vehicles batteries is presented as a promising way to exploit the residual capacities of this type of batteries. In [15] an economic analysis of reused electric vehicle batteries in a photovoltaic system distributed under shared commercial models has been carried out. And, as the latest example of current research in the field of reusing electric vehicle batteries in storage systems, recent research [11] has proposed a two-stage optimization of a wind energy storage system built using second-life batteries to participate in both the spot market and the reserve market of normal operation of frequency containment and, with this, be able to increase the profits of the owner of the wind farm.

In short, the role that energy storage can play in a current generation system is even more important in island systems, such as the island of Tenerife, which is why the use of the proposed technology is even more interesting in this type of systems [23]. From an economic point of view, an insular isolated electrical system supplied with fossil fuels presents high costs derived from the importation and transport of the same and the need to maintain a greater capacity of electricity generation to ensure the stable supply [24][25]. Given this scenario, and due to the importance of energy management and independence of isolated territories, on islands with a good source of wind and sun, it will be more sustainable and cheaper to produce energy with renewable technologies than with conventional energy sources. This situation would be possible to a greater extent through the use of energy storage systems [26].

In this work, the potential of battery energy storage systems to support a greater integration of renewable energies has been investigated. Specifically, the use of battery energy storage systems in wind farms has been studied, with the aim of increasing the robustness of isolated electrical systems located in geographic locations that have a good wind resource. More specifically, the feasibility of using second-life electric vehicle batteries for their application as an energy storage system has been studied. The study has focused on the potential of these batteries to avoid "wasting" energy from the wind, due to the power reductions established by limitations in electricity demand. The study has focused on the island of Tenerife, Canary Islands, Spain.

After a brief introduction, Section 2 describes the theoretical framework on which the challenges of integrating variable renewable energies in electrical grids are based, as well as the fundamentals of the electrical energy storage systems available today. Then, in Section 3, the methodology to be followed is detailed: firstly, to study the role of wind energy in the electricity generation structure of the island of Tenerife; second, to analyse electric mobility on the island under study; and, finally, simulate the use of second-life electric vehicle batteries as an energy storage system in a real wind farm in Tenerife, so that a technical and economic feasibility study of the proposal could be carried out. Section 4 presents the results obtained in the first of the studies carried out, answering questions such as: How is the electricity generation structure on the island of Tenerife? What is the installed wind capacity? How much wind energy per year is fed into the grid? What are the forecasts for the annual penetration of wind energy in the grid for 2030? Section 5 shows the results obtained in the second analysis carried out, responding to the following: What has been the evolution of electric mobility in Tenerife in recent years? How is it expected to evolve towards the year 2030? What energy storage capacity based on second-life batteries is expected between the years 2025-2030? Section 6 summarizes the results of the project of technical and economic feasibility of the proposed system, being able to find an answer to: How much wind energy is “wasted” due to the set points due to the limitations exposed by the electricity demand? What storage capacity is necessary to cover this "energy waste"? Can the economic losses due to the slogans imposed by REE on wind farms justify the investment necessary for the installation of an energy storage system? Is the reuse of batteries removed from electric vehicles appropriate for this application? Finally, Section 7 concludes the entire document.

2. Theoretical Framework

Energy is the basis of the welfare state, the economy and the development of societies. In fact, population growth, industrial development, and economic growth lead to increased demand for energy. On the other hand, increasing energy demand leads to environmental challenges such as global warming and climate change, the health impacts of air pollution, and the risk of soil and water contamination [27].

Climate change has become one of the main concerns of this century. The Paris Agreement establishes efforts to limit global temperature rise to 2°C and ideally 1.5°C in this century. For this, a profound transformation in the global energy landscape is essential, which will not be possible without the rapid deployment of low-carbon technologies that replace the generation and uses of conventional fossil fuels. To meet the targets, CO_2 emissions related to the energy sector have to be reduced by around 3.5% per year from now until 2050, maintaining a continuous reduction in subsequent years. The transition towards an increasingly electrified form of transport and heat, increases in the generation of renewable energy and energy efficiency are fundamental pillars to increase the chances of achieving the established objectives [1].

According to a recent analysis by the International Renewable Energy Agency, the renewable share of global power generation is expected to grow from 25% today to 86% in 2050. Growth is especially strong for variable renewable technologies, mainly solar photovoltaic and wind, with a 4.5% increase in power generation in 2015 to around 60% in 2050 [28].

2.1. Integration of variable renewable energies

Existing electrical grid systems globally are not equipped to handle the large-scale integration of intermittent power sources without serious grid outages. It is generally accepted that a penetration of more than 20% from intermittent renewables energies can greatly destabilize the grid [29]. The intermittent nature of renewable energy resources and energy fluctuations over multiple time horizons increases the complexity of grid planning and operation [30], which translates into a significant impediment to reliable electricity generation and to its massive deployment worldwide [29]. Renewable energy plants must meet certain codes and requirements to be able to connect to the grid, with compliance with the ramp rate being one of the most challenging requirements, especially for photovoltaic or wind power generation plants [31].

To manage the integration of high amounts of variable renewable energy it is necessary to take advantage of flexibility in all sectors of the energy system, from power generation to transmission and distribution systems, storage and, increasingly, flexible demand, in other words, the management of the demand side coupled to the sector. Technical solutions to variable renewables integration challenges almost always exist, so the limitation is largely economic rather than technical. Therefore, economically speaking, the maximum ideal level of variable renewable energy integration is one in which any additional costs outweigh the benefits obtained by an additional renewable unit [32]. Fortunately, the flexibility of power system is not static. Innovation can increase the flexibility of the energy system throughout the value chain, including supply, transmission, distribution and demand, while reducing total system costs. However, nowadays there is no lack of innovation; instead, we need to find ways to make sense of recent innovations and publications. No single innovation can have a significant impact, but must be accompanied by innovations in all segments of the electricity sector. More flexible and integrated energy systems are needed to maximize the value of low-cost renewables [25].

On the other hand, the main technical challenges that may arise when integrating high quotas of renewable energy into island energy systems are: ensuring sufficient firm capacity, to ensure that the generation fleet can still reliably supply the electrical load throughout timing (generation adequacy); address flexibility needs, in order to accommodate intraday variations in the net load with the generation system, driven mainly by the variability and uncertainty of variable renewable energies; and, ensuring system stability, which is an important technical concern when targeting high quotas of variable renewable energy in small power systems [24].

All these challenges require some type of energy storage device to develop viable power system operation solutions [30]. Rapid, utility-scale deployment of intermittent sources is highly dependent on the availability of cost-effective, efficient, and scalable energy storage technologies [29]. Bloomberg Technology News reported on July 31, 2017 that Germany had to scrap 4% of its wind energy in 2015 and China has scrapped 17% of its renewable energy, while California had to give up 300,000MWh of solar and wind energy in the first half of 2017, all due to the lack of sufficient electricity storage capacity [33].

Certainly, energy storage technologies are providers of flexibility throughout the energy sector, with great potential to enable high shares of variable renewable energies in the system. The cost of storage continues to decline, allowing accelerated deployment for today's applications and becoming a provider of new services for power systems [25]. Electrical energy storage systems can alleviate many of the inefficiencies and deficiencies inherent in the electrical grid and help improve grid reliability, facilitate full integration of intermittent renewable sources, and effectively manage power generation. Electrical energy storage offers two other important advantages. First, it decouples electricity generation from load, making it easier to regulate supply and demand. Second, it enables distributed storage opportunities, which greatly improve network security and thus energy security [29]. Some of the significant applications of energy storage are: battery charging to avoid the reduction of excess generation, provision of auxiliary services, provision of reserve capacity, reliable power supply for isolated grids and compensation of transmission and distribution upgrades [25].

2.2. Electrical energy storage systems

Currently, there are an estimated 4.67TWh of electricity storage. More than three-quarters of energy storage capacity was installed in just ten countries, and only three, China (32.1GW), Japan (28.5GW) and the United States (24.2GW), account for almost half (48%) of the world's energy storage. Pumped hydro storage dominates both total installed power capacity and energy storage capacity. Pumped hydroelectric storage represents 96% (176GW) of the total installed storage power capacity globally as of mid-2017. The remaining electricity storage technologies, which are already in significant use worldwide, include thermal storage, with 3.3GW (1.9%); batteries, with 1.9GW (1.1%) and other mechanical storages with 1.6GW (0.9%) [34].

With the growing demand for electricity storage from stationary and mobile applications, the total stock of electricity storage capacity in energy terms should grow from an estimated 4.67TWh at present to 11.89-15.72TWh if the share of renewable energies in the energy system will double by 2030. In fact, the capacity of battery energy storage systems in stationary applications by 2030 must increase by a factor of at least 17 compared to the current estimated level, to meet the requirements for doubling renewables in the global energy mix [34].

For renewable energy to achieve being a primary energy source by mid-century, electricity storage technologies must satisfy key requirements including: high capacity, fast charge/discharge rates, high density of power, long life cycle, stable operation and performance, reliability, cost-effectiveness and easy expansion [29]. There are different types of electrical energy storage systems with different costs, operating characteristics, and potential applications. Understanding these systems is vital for the future design of power systems, whether for short-term transient operations or long-term generation planning [30]. Electrical energy storage systems can be classified into four main groups [27]:

- Mechanical systems; such as pumped hydro storage (PHS), compressed air energy storage (CAES) and flywheel energy storage (FES).
- Chemical systems; such as hydrogen storage with fuel cell/electrolyzer, synthetic natural gas (SNG) and reversible chemical reactions.
- Electrochemical systems; in particular, different types of batteries or battery energy storage systems (BES).
- Electric systems; They include capacitors, supercapacitors, and superconducting magnetic energy storage (SMES).

There is no single winning technology for energy storage. Each offers its own strengths and weaknesses, as well as a clearly different technical basis that governs its operating principle [29]. Therefore, some systems are appropriate for specific applications, while others can be chosen for broader applications [27]. To be effective for a specific application, a storage technology must have the appropriate technical characteristics as response time, power capacity and energy capacity or synchronous inertia capacities [28]. Figure 1 shown a comparison of different types of electrical energy storage systems in terms of output power, module size and discharge time.

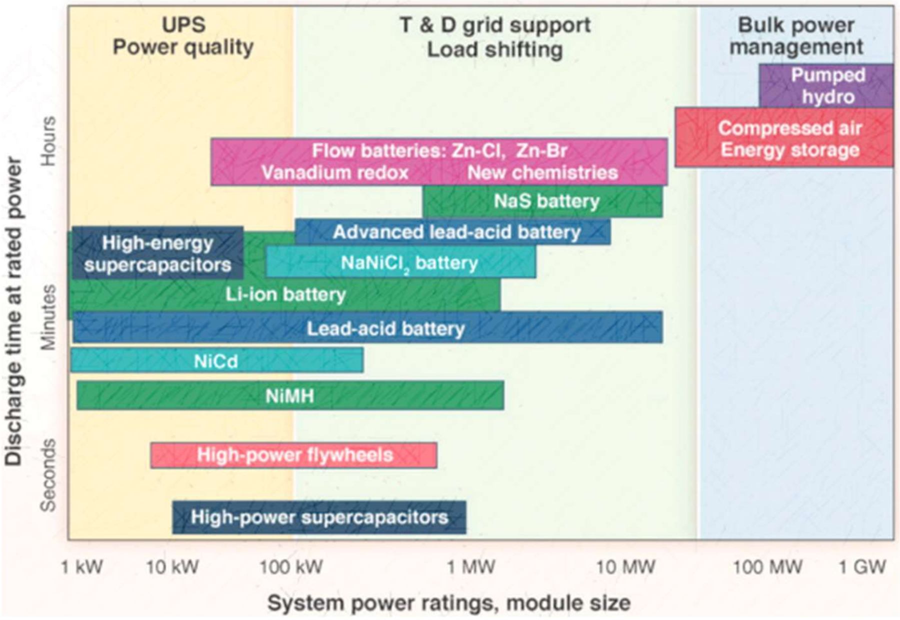

Figure 1. Comparison of different types of electrical energy storage systems. Source: [27]

Figure 2 indicates the commercial maturity of different electrical storage technologies. Pumped hydroelectric energy storage, compressed air energy storage and lead-acid batteries are the technologies with the greatest maturity.

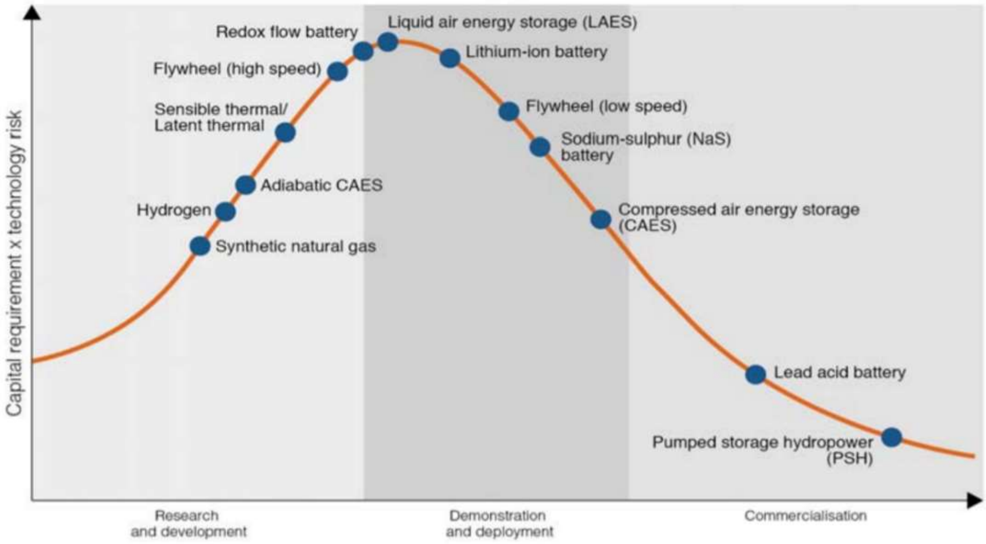

Figure 2. Commercial maturity of different electrical storage technologies. Source: [35]

2.3. Electrochemical energy storage systems

Electrochemical energy storage systems are the oldest and most extensive energy storage technologies that also represent one of the fastest growing market segments. In these systems, a reversible chemical reaction is used in an active material through an electrolyte to produce/store energy in direct current [30][34]. Specifically, for electrochemical storage, the systems require two specialized bodies of electrodes separated by an electrolyte. Electrodes are preferably chosen from abundant and inexpensive materials that exhibit good electronic conductivity, good stability, and high catalytic activity [29].

Batteries will undoubtedly play an important role in integrating intermittent renewable sources. Costs and environmental impact aside, battery energy storage systems are the most effective technology for stabilizing power grids that access significant amounts of renewable energy (> 10%) [27]. By coupling a specific renewable energy source with a battery, the variability of the output power at the grid interconnection point is reduced, facilitating better integration into the grid. The battery energy storage system can smooth the output of variable renewable energy systems and control ramp speed to eliminate voltage and frequency fluctuations in the power grid. Furthermore, due to generation smoothing, renewable energy generators can increase compliance with their generation schedules and avoid paying fines for any deviation in generation output. Generation smoothing would also allow renewable energy generators to take better positions in market-based energy/power auctions, due to greater certainty and 24-hour power availability [25].

The global installed capacity of large-scale battery energy storage systems in mid-2017 was 10GWh. Key countries for large-scale battery utilization include Australia, China, Germany, Italy, Japan, Republic of Korea, the UK and the US. Notably, in November 2018, PG&E in California awarded the two largest battery contracts in the world to date, with 300MW/2,270MWh and 182MW/730MWh. It is also interesting to mention the case of a Portuguese island, Graciosa, which has reduced its dependence on imported fossil fuel and, in turn, has been able to reduce greenhouse gas emissions, thanks to the implementation of a 1MW solar photovoltaic plant, a 4.5MW wind power plant and a 6MW/3.2MWh battery storage system. The plant can currently meet 70% of local demand, while eliminating the need for around 17,000 liters of diesel per month [25].

The different types of battery energy storage systems can be classified into two groups: integrated battery energy storage systems (lead-acid, lithium-ion, sodium-sulfur, nickel-cadmium batteries) and external battery energy storage systems (vanadium redox flow batteries, ZnBr and Zn-air systems). In the first group mentioned, there is no spatial separation between the energy conversion unit and the active material where the charge/discharge occurs directly. In the second group, the energy conversion unit and the active material are physically separated from each other. Among the many types of battery energy storage systems available, we cannot unequivocally state that one particular system is better than another. Depending on the power of the application and the power ratings, size, weight, response time, depth of discharge, operating temperature, and ambient temperature, one type of battery should be chosen over another [30]. In this work we will focus on the study of lithium ion batteries, due to their widespread use in electric vehicles. To obtain information on other types of batteries (lead-acid, sodium-sulfur or flow batteries), it is recommended to go to publications such as [29] and [27], in which a broad review of the different technologies existing today is carried out.

2.4. Lithium ion batteries

Although there are a number of emerging battery energy storage technologies with great potential for further development, lithium-ion batteries account for the majority (59%) of installed operating capacity as of mid-2017 [27][34]. Furthermore, it is the most established large-scale battery energy storage technology with 90% of the current total installed capacity for large-scale battery storage [25]. Arguably one of the most notable technological achievements in electrochemistry in recent years is the successful commercialization of lithium-ion batteries, which has had a profound impact on the widespread use and deployment of portable electronic devices and, more recently, in transport and stationary storage [29].

Lithium-ion batteries are lighter, smaller and more powerful than other batteries, making them a more attractive proposition for consumer electronics. In addition, there are currently more than 300MW of lithium-ion battery projects. High-power, short-life utility-scale lithium is installed worldwide for frequency control application, in addition to microgrid integration support for high-power intermittent renewable energy resources. In particular, the last decade has seen a growing trend toward next-generation lithium-ion batteries with high charge power/energy densities developed for electric vehicles, hybrid electric vehicles, aerospace applications and autonomous electrical devices [27][30][36][37].

Li-based battery systems are attractive because Li is the most electropositive element on the periodic table (redox potential = −3.05V) and the lightest metal (6.94g/mol), thus offering high energy density. In fact, the theoretical energy density of lithium-ion batteries is about 380Wh/kg, while commercially available rechargeable lithium-ion batteries provide 150-210Wh/kg. Power densities vary in the range from 500 to 2000W/kg, with efficiencies around 90%. As the Li^+ ion also has a small ionic radius (90 pm), it allows fast diffusion rates through the electrode material, offering fast charge and discharge rates. Ultimately, lithium-ion batteries are characterized by high energy and power density with respect to volume per unit, stable cycle, low self-discharge rate, long useful life, wide operating temperature range, light weight, wide design flexibility, near zero memory effect, high open circuit voltage, fast charge/discharge, fast response time (in milliseconds), high efficiency and sealed cells requiring no maintenance. In addition, over the years, there has been a significant decrease in cost with regard to increasing the specific density of energy and power of the lithium-ion battery, thus less material is required for the manufacture of the same amount of power cell. However, lithium-ion batteries are fragile, require a special protection circuit to avoid overcharging, require frequent charging, and have a high capital cost, which limits their use for high-capacity applications. Furthermore, the useful life of lithium-ion batteries is sensitive to over discharge, high temperatures (above 45°C) and aging. And, under charged conditions, lithium-ion batteries are extremely sensitive to high temperatures, overcharging, and internal pressure build-up [27][29][30][36][37][38].

Design flexibility involves the selection of salts used as the electrolyte. Conventional lithium ion batteries are mainly based on the Li^+ intercalation mechanism ($LiCoO_2$, $LiPF_6$, $LiFePO_4$ y $LiMn_2O_4$). Among all lithium ion batteries, Lithium iron phosphate batteries are considered the most economical and widely applied in electric vehicles. However, these lithium ion batteries cannot offer the high charge capacities (> 200mAh/g) needed for particular applications. For this reason, recently, researchers have shown an immense interest in high energy density battery technologies, such as those rich in Li ($Li_{1.2}\,Mn_{0.54}\,Ni_{0.13}\,Co_{0.13}\,O_2$) and transition metal oxides rich in Ni ($LiNi_{0.8}\,Co_{0,15}\,Al_{0,05}\,O_2$ o $Li\,[Ni_{0,8}\,Co_{0,1}\,Mn_{0,1}]\,O_2$), high-voltage spinels and Li-sulfur batteries, Li-air, organic electrode, Li-CO_2 and solid state. They benefit not only from the high load capacity, but also from the lower cost. Additionally, they are less toxic compared to widely marketed lithium ion batteries (e.g., $LiCoO_2$). However, there are crucial issues that must be addressed for its successful commercialization (e.g., phase transition, electrolyte breakdown, or formation of an unstable solid-electrolyte interface) [27][30][37].

The cost of lithium-ion batteries has dropped by as much as 73% between 2010 and 2016 for transportation applications. Lithium-ion batteries in stationary applications have a higher installation cost than those used in electric vehicles due to the more challenging charge/discharge cycles that require more expensive battery management hardware and systems. However, benefiting from the growth in the scale of the manufacture of lithium-ion batteries for electric vehicles, the cost could decrease in stationary applications by another 54-61% by 2030. In other words, the total cost of installing lithium-ion batteries for stationary applications would be between 120€/kWh and 400€/kWh. As installation costs decline, continual technology improvement will increase performance. The life of lithium-ion batteries could increase by about 50% by 2030, while the number of possible full cycles could increase by up to 90%. At the same time, efficiencies will improve a couple of percentage points, hovering between 88% and 98%, depending on battery chemistry [34].

2.5. Disposal and recycling of batteries

Batteries generate environmental pollutants, including hazardous waste, greenhouse gas emissions, and toxic fumes during their manufacture, use, transportation, collection, storage, treatment, disposal, and recycling. Collecting, recycling and disposing of batteries is a huge challenge, as most are currently sent to landfills at the end of their useful life, rather than being collected and recycled. Most of the materials that make up batteries can be recycled, although not cheaply, using chemical and mechanical techniques. Recycling of used batteries reduces production costs, consumption of raw materials and environmental impacts. Despite this, the biggest challenge for recycling is collection, since it depends on the contribution and support of society, government, companies and other social organizations [27].

Batteries are produced from a variety of materials, including metals, non-metals, plastics, paper (or cardboard), and electrolytes. The global consumption to make batteries represents large fractions of lead, cadmium, cobalt, lithium, antimony, lanthanum and graphite [27]. With the increasing use of battery energy storage technologies, the availability of raw materials, particularly for use in lithium-ion battery systems, has gained much attention in recent years. However, a shortage of lithium appears unlikely in the near future [34].

Currently, lithium-ion battery recycling is limited (less than 3%), but with a growing demand for electric vehicles and restricted access to virgin materials, recycling of these types of batteries has become a vital issue. There are three general methods for recycling lithium-ion batteries: mechanical, pyro-metallurgical, and hydrometallurgical processes. These methods are mainly intended to recover different materials: lithium, copper, cobalt, nickel, iron, aluminum and manganese [27].

2.6. Second-life electric vehicle batteries

As discussed in the Introduction section, electric vehicles are presented as a solution for the de-carbonization of the transport sector and it is expected that, in the coming years, their use will spread until they dominate the automotive market [13][14]. According to the Baden-Württemberg Research Center for Solar Energy and Hydrogen, there were 5.6 million electric vehicles on the world's roads at the beginning of 2019. China and the United States are the largest markets, with 2.6 million and 1.1 million electric vehicles respectively. On average, electric vehicle sales grew rapidly during the period 2012 to 2017, with a compound annual growth rate of 57%. However, the market is still in an early phase, as electric vehicles represent only 1.3% of all light vehicles sold in 2017. Policy support plans and international, national and private commitments on the deployment of electric vehicles are the main drivers of market adoption [39].

Lithium-ion batteries are one of the key technologies to enable the techno-economic feasibility of mass adoption of this type of vehicle. However, minimizing their environmental impact is vital, as current projections for electric vehicle uptake indicate that, globally, several gigawatt hours of used batteries are likely to be removed from electric vehicles annually by 2030. This hypothetical situation poses a great challenge for battery recycling facilities in the future [16].

An alternative to recycling recalled electric vehicle batteries is to recondition and reuse them in stationary applications [11]. The electric vehicle demands a high performance from its batteries, so when they decrease their capacity by 20-30% they must be replaced. However, in this state of capacity, the recalled batteries can still handle a good amount of charge/discharge and can therefore be used in other less demanding applications in terms of performance, volume and weight. The second-life battery concept refers to those batteries that are removed from electric vehicles when their energy density cannot cope with motor applications, but are still efficient enough for stationary applications [16].

This second life offers an extension of up to 10 years in battery life, at a compelling price, which 2019 is estimated at around 110€/kWh. The advantages of second-life battery storage are: additional monetization of the battery after it served the primary purpose in an electric vehicle; savings in the manufacture of new battery cells; and, delay in recycling a battery with approximately 70% remaining capacity, which is potentially wasteful, postponing related regulatory responsibilities [39]. The benefits of second-life use can only be realized once certain drawbacks are addressed: the cost of reconditioning a used electric vehicle battery (which involves testing and adjusting the voltage of the packs); shorter service life and lower efficiency as a result of degradation during the first life; warranty issues and social and regulatory barriers to the adoption of second-life batteries. Furthermore, it is possible that electric vehicle batteries that have been in use for 10 years or more may be technologically obsolete, making them more suitable for recycling rather than reuse for second-life use [16][39]. Not all cells may be eligible for possible second life use, and proper tracking of first life battery aging data is crucial in selecting the most suitable second life batteries. Therefore, the commitment and collaboration of the automotive Original Equipment Manufacturers would be vital for a well-founded battery selection and for second battery life to be a technically viable concept [21].

Reference is made in [39] to a number of examples of secondary storage products and demonstrations from car manufacturers. The following projects should be highlighted: the sale of new and recycled batteries by the manufacturer BYD, in China and Australia, with the aim of offering backup power for telecommunications towers, solar energy street lamps and low-speed electric vehicles; and, the project carried out in January 2018, by Nissan, which launched a new solar power generation and energy storage system for domestic use in the United Kingdom (UK). The automaker claims that its solution enables UK homeowners to increase the self-consumption rate of on-site PV and reduce energy bills by up to 66%. More than 880,000 UK homes already have solar panels and the market is growing. This new product is a further extension of x-Storage Home that Nissan developed in partnership with Eaton with second-life electric vehicle batteries.

3. Experimental: Second-life electric vehicle battery wind energy storage systems in isolated electrical systems

In this work, the potential of battery energy storage has been investigated to support a greater integration of renewable energies and the use of second-life electric vehicle batteries has been proposed to design low-cost electrical energy storage systems. The batteries will be reused to store surplus wind energy at times of low electricity demand and high wind resources, with the aim of avoiding power reductions. Furthermore, these hybrid systems consisting of wind farms and battery energy storage systems are expected to increase the robustness of isolated electrical systems located in geographic locations with a good wind resource. It has been chosen to incorporate the proposed system in isolated electrical systems due to their greater vulnerability to the stochastic and intermittent nature of renewable energies, especially wind energy. Specifically, the study carried out has focused on the island of Tenerife, Canary Islands, Spain.

To carry out the aforementioned study, two powerful software tools have been used:

- Excel, a computer program developed and distributed by Microsoft Corp, widely known and used to perform accounting and financial tasks thanks to its functions.
- Python, an object-oriented open source programming language, which has a vast library of tools. Python allow you to create highly readable code, which saves time and resources, facilitating its understanding and implementation. In addition, in the case at hand, Python is a very useful and powerful programming language for Big Data, Data Science and Artificial Intelligence tasks.

The research carried out has been divided into three sections: wind energy in the electric system; electric mobility; and, technical-economic feasibility of a second-life electric vehicle battery energy storage systems in a wind farm.

3.1. Wind energy in the electric system

The current energy mix of Tenerife, the role that wind energy plays in the structure of electricity generation and the expected evolution in the integration of wind energy in the island's electricity grid by the year 2030 have been studied in depth.

For this, possible sources of reliable data on the electrical system of the island of Tenerife have been investigated. After the investigation carried out, it was concluded that the best source of data that we could consult for the aforementioned purpose is the operator of the electricity system in Spain, that is, *Red Eléctrica España* (REE). REE has the task of ensuring the global operation of Spanish Electrical System through the operation of the electrical system and the transmission of high voltage electricity. Furthermore, as the operator of the electricity system, it must guarantee the continuity and security of the electricity supply and the permanent balance between the production and consumption of electricity.

Specifically, an information system called the System Operator Information System (e-sios) has been consulted. It has been designed by REE to execute the processes that allow the safe and economic exploitation of the Spanish Electricity System in real time. According to current legislation, the electricity system operator has the obligation to make public the results of the markets or system operation processes, guaranteeing at all times the secrecy of the confidential information made available to it by the market subjects. To this end, the REE has developed and published a public website: e-sios [40], where the public information resulting from the operating processes under its responsibility is made available to anyone. This information system is capable of storing both the information that enters the system and that resulting from the different processes, in its Historical Database.

Thanks to this, we have been able to access the following historical databases:

- Monitoring of electricity demand (MW). This historical database details the real, projected and programmed power consumption in the Tenerife electrical system from 01/01/2015 to 05/31/2020, with a total of 284,548 ten-minute data columns.
- Generation structure (MW). This other historical database provides the power offered by the different generation technologies installed on the island of Tenerife (diesel engines, gas turbines, wind, combined cycle, steam turbine, photovoltaic solar) since 01/01/2015 to 05/31/2020, also with a total of 284,548 ten-minute data columns.

In addition, it has been possible to access the installed power by technology (MW) on the island of Tenerife, as well as the location of each of the currently active generation facilities, thanks to a mapping of the distribution of the generation in Tenerife made by REE.

3.1.1.Data Analysis

Once the databases used in this first study have been defined, the data analysis was performed:

1) The datasets have been cleaned and processed. Datasets do not always have the necessary format or completeness to be analysed properly. The cleaning process consists of removing or replacing elements of a dataset in a way that affects the final results as little as possible. We will use the Python *Pandas* library to perform the data cleaning process. It is an open source, BSD-licensed library providing high-performance, easy-to-use data structures and data analysis tools for the Python programming language. In other words, *Panda*s is a library qualified to process high-level data in Python (that is, statistics), since it has the data structures necessary to clean raw data and make it suitable for analysis. Some of the functions used in the cleaning process are: *Pandas drop_duplicates()* method, that helps in removing duplicates from the data frame; or *Pandas dropna()* method, that allows the user to analyse and drop Rows/Columns with Null values in different ways.
2) Taking advantage of the availability of the map with the distribution of the generation in Tenerife available in the System Operator's Information System, a count of each of the active installations has been made, in order to provide a summary of the installed power by technology and by municipality on the island under study. In this way, it has been observed how centralized the generation on the island is under analysis, as well as knowing what type of generation predominates in its electrical system at present. In addition, through this study, the participation of wind power in the total installed power in Tenerife has been obtained, which has allowed us to know what is the state of maturity of this type of energy in the scenario studied.
3) An analysis of the databases extracted from e-sios has been carried out. For this, the *Pandas* library has also been used, due to its usefulness for processing high-level data in Python. Before carrying out the analysis, both databases (demand monitoring and generation structure) have been combined, since they have the same data frequency and the same time index. This was made possible by the *pandas.concat()* function, which is used to concatenate objects along a particular axis with optional set logic along the other axes. To begin with the statistical analysis or summary of the data set on demand and generation in Tenerife's electricity system, the *dataframe.describe()* method has been used. This function allows us to calculate some statistical data such as percentile, mean and standard deviation of the numerical values of a Series or Data Frame. Furthermore, this process allows us to obtain the average of the electricity demand in the study period, that is, between 2015-2020, to observe which has been the highest demand for electricity or, on the other hand, to be able to observe the highest injection of wind power in the electrical grid in recent years.

4) Average load curve for the Tenerife power system has been made. For this, the arithmetic mean of 2015-2020 data set (electricity demand, wind power, photovoltaic power, etc.) per hours has been obtained. This calculation required the use of the *Numpy* library and the *dataframe.between_time()* function in Python. On the one hand, *Numpy* is an open source python library used for working with arrays. It also has functions for working in domain of linear algebra, Fourier transform, and matrices. *Numpy* aims to provide an array object that is up to 50x faster than traditional Python lists. Arrays are very frequently used in data science, where speed and resources are very important. On the other hand, *dataframe.between_time()* is a *Pandas* method that is used to select values between particular times of the day (e.g. 9:00-10:00 AM).

5) Annual evolution of generation in terms of energy (MWh) by technology between 2015 and 2020 has been analysed. Taking into account that our dataset is about several time series, that is, series of points of data indexed in time order, we have changed the temporal frequency of our series. Specifically, it has gone from a ten-minute frequency to an hourly frequency. With this, we have been able to obtain new time series on the monitoring of demand and generation structure in Tenerife in terms of energy (MWh) instead of in terms of power (MW). This has been possible thanks to the application of the *dataframe.resample().mean()* function present in the *Pandas* library. This method is used primarily for time series resampling. Resampling generates a unique sampling distribution based on the actual data. This is a very important technique in the field of analytics. In the present case, we have applied the hourly frequency to our time series, making an average of the initial data. Once we had the demand and generation data in terms of energy, we have applied the same resampling function to our new hourly dataset, but this time applying an annual frequency, so that the sum of the hourly values obtained previously. The applied function is the following: *dataframe.resample('Y').sum()*. With this, we have obtained a data matrix detailing the demand and generation structure in Tenerife by technology and by year, from 2015 to the present.

6) We have focused on studying the trend of wind generation (MWh) in Tenerife between 2015 and 2020. As we have previously mentioned, our dataset is about different time series. In this case, we will focus on one of them, wind generation. To carry out this study, we will start from the new dataframe generated in the previous section, which shows the values of wind generation with an hourly frequency. However, in order to be able to work with a smaller amount of data, it was decided to transform the time series to be analysed on a monthly frequency. This operation has required a similar procedure followed in the previous point. More specifically, we have applied the following function: *dataframe.resample('M').sum()*. Next, in order to be able to more clearly visualize the variation in the monthly generation of wind energy over the years, the average monthly generation of wind energy has been calculated by year, from 2015 to 2020. To do this, the *dataframe.resample().mean()* function has been applied again.

   The trend is an upward or downward movement of data over time over a long period. Time series data often show slow and gradual variability in addition to higher frequency variability, such as seasonality and noise. An easy way to visualize these trends is through rolling means. In statistics, a rolling mean is a calculation used to analyse a dataset in point mode to create series of averages. Thus rolling mean are a list of numbers in which each is the average of a subset of the original data. A series of moving averages can be calculated for any time series. In short, the moving average is a trend indicator that never anticipates the movement of data, that is, it simply follows the stock curve confirming the current trend at all times. It does not anticipate trend changes, but it can confirm them. To apply this concept to our study, we have used the *Pandas dataframe.rolling().mean()* function that returns the calculation of the moving average of the values of the time series to be analysed. It should be noted that it is essential to define the "window" parameter of the *rolling()* function, since it is the size of the moving window, that is, the number of observations used to calculate the statistics. In this case, the value of the mentioned parameter will be 12, since it is the number of observations per year of our time series. Additionally, the moving standard deviation has been calculated as an indicator of the volatility of the analysed data. This has been done using the *dataframe.rolling().std()* function.

3.1.2. Wind energy contribution model

Finally, the annual generation of wind energy has been planned in Tenerife from 2020 to 2030, with the aim of studying the evolution of the participation of this type of energy in the island's electrical system in the future. To carry out this last step, it has been chosen to use a regressive method of analysis of time series. Specifically, the SARIMA model, short for 'Seasonal Auto Regressive Integrated Moving Average'. This method explains a given time series based on its own past values, making use of seasonal differentiation.

A SARIMA model is characterized by the following parameters:

- "p" is the order of term 'Auto Regressive' (AR). It refers to the number of lags in the time series that will be used as predictors.
- "q" is the order of term 'Moving Average' (MA). Refers to the number of lagged forecast errors that should be included in the model.
- "d" is the amount of differentiation required to make the time series stationary. If the time series is already stationary, then d=0.
- "P" is the order of term 'Seasonal Auto Regressive' (SAR). It refers to the number of lags in the time series that will be used as predictors, taking into account its seasonality.
- "D" is the order of seasonal differentiation.
- "Q" is the order of term 'Seasonal Moving Average' (SMA). It refers to the amount of lagged forecast errors that should be included in the model taking into account the seasonality of the time series studied.
- "S" is the time frequency of the time series.

To adjust these parameters, the function of *auto_arima()* in Python has been used. This function searches for multiple combinations of the parameters that define the model through a gradual study and takes as the best model the one with the lowest Akaike information criterion (AIC), which is a measure of the relative quality of a statistical model, for a given set of data. The results of this model are shown in section 4.

3.2. Electric mobility

The evolution that the electric vehicle fleet has suffered during the last decade has been studied, as well as the possible growth of said fleet over time, in order to observe the potential of the research carried out in a future scenario. This study is fundamental, since it has allowed forecasting the availability of batteries removed on the island and, therefore, we have been able to estimate the capacity of second-life electric vehicle batteries that will be available in the next decade, this is, by the year 2030.

For this, as was done in the first study, possible sources of reliable data on the vehicle fleet in Spain have been investigated. After the investigation carried out, it was concluded that the best source of data that we could consult is the Central Traffic Headquarters in Spain, this is, *Dirección General de Tráfico* (DGT). It is an Autonomous Organization of those provided for in article 98 of Law 40/2015, of October 1, on the Legal Regime of the Public Sector, whose purpose is the development of actions aimed at improving the behaviour and training of road users, and the safety and fluidity of vehicle circulation and the provision to the citizen of all administrative services related to them.

Specifically, the DGT Statistical Portal [41] has been consulted. It is a space that aims to satisfy, in an agile, fast and dynamic way, the growing demand for statistical information related to the activity carried out by DGT. Vehicle and driver statistics are currently available. Thanks to this, we have been able to access the following historical databases:

- Vehicle fleet in the province of Santa Cruz de Tenerife for the years 2010, 2015, 2016, 2017, 2018, 2019 and 2020. This is a series of .csv files in which a table is provided that summarizes an analysis of the number of vehicles in circulation for each year and their technical characteristics, such as the type of vehicle or the type of fuel it uses.

- Monthly vehicle registrations in Spain. Data has been downloaded from January 2015 to May 2020. These databases are variants and quite extensive, since they have very complete information. Data are provided on: registration date, vehicle brand, vehicle model, vehicle type, propulsion type, vehicle's fiscal power, weight, number of seats, registration province, vehicle domicile province, etc. In summary, they allow the knowledge of the vehicles that are registered in circulation and their characteristics, as well as their impact on the fleet of vehicles in circulation. An interface document for sending registration data, provided by the DGT, will be attached as APPENDIX I, detailing the format and content of the downloaded files.

3.2.1.Data Analysis

Once the databases used in this second study have been defined, the data analysis was performed.

1) The downloaded files with the fleet of vehicles in the province of Santa Cruz de Tenerife have been unified to obtain a better view of their evolution. Next, the data has been filtered using a dynamic table in Excel and the vehicle fleet has been compared according to the year, the type of vehicle (tourism, bus, motorcycle, etc.) and the type of fuel used (diesel, gasoline, electric, etc.). It should be noted that special importance has been given to the analysis of the existing electric vehicle fleet in the province under study.

2) The different data files with monthly registrations in Spain have been combined according to the year and, then the import of this database has been carried out, taking into account what is stated in APPENDIX I. Once the databases were imported, they have been cleaned and treated. For this, we have used the Python *Panda*s library, just like in the first study. With the databases suitable for analysis, we have filtered the data set according to vehicle domicile province. In this way, we have only kept those vehicles that are domiciled in the province of Santa Cruz de Tenerife. This has allowed us to generate a new DataFrame of smaller size and with which we can work more efficiently.

3) The data has been filtered based on the vehicle's propulsion type. Specifically, we have only with those registered vehicles whose propulsion is electric. In this way, a new database has been created with only electrically powered vehicles domiciled in the province of Santa Cruz de Tenerife. More specifically, we have generated six databases, one for each year studied, taking into account that the years between 2015 and 2020 have been studied.

4) It has been chosen to perform cross tabulations of various factors. In other words, a series of frequency tables have been generated between factors such as: vehicle domicile municipality, vehicle type, vehicle model, vehicle brand, electric vehicle category or the service provided by the vehicle. For this, the *Pandas* library has also been used, since it offers several options to group and summarize data. In this case, the *pandas.crosstab()* function has been used to create crosstab tables to show the frequency with which certain groups of data appear. Specifically, the following cross-tabulations have been made: vehicle domicile municipality-vehicle model, vehicle type-vehicle brand, vehicle type-vehicle service, electric vehicle category-vehicle brand. The procedure has been repeated for each year studied. In this way, it has been possible to obtain very useful information for the research carried out, for example: which municipalities in the province of Santa Cruz de Tenerife have a higher registration rate for electric propulsion vehicles or which are the model and brand of vehicle with higher registration rates for electric vehicles in Santa Cruz de Tenerife.

5) Trend of monthly registrations of electric vehicles in Tenerife between 2015 and 2020 has been studied. For this, the databases on registrations of electric vehicles described above have been converted into a time series in which the number of electric vehicles registered in the province of Santa Cruz de Tenerife for months from January 2015 to May 2020. This has been done thanks to the tools available in the *Pandas* library in Python. It will not go into more detail, as many of its functions have already been mentioned and explained previously.

Once we have summarized our database in a time series, we have proceeded to calculate indicators of the trend of the data, such as the annual average of monthly registrations of electric vehicles and the moving average, as was done in the study of the trend of the monthly generation of wind energy (MWh) in the electricity system of Tenerife. Additionally, the mobile standard deviation has been calculated as an indicator of the volatility of the analysed data, as was also carried out in the first study of wind generation in Tenerife.

3.2.2. Capacity of second-life electric vehicle battery energy storage systems

Forecasting of availability of batteries removed from electric vehicles has been carry out on the island of Tenerife and the capacity of second-life electric vehicle batteries that will be available in the next decade has been estimated. To do this, we have studied the technical sheets of those brands of electric vehicles with a higher registration rate, as obtained in the previous section, and we have investigated the characteristics of the batteries used in these vehicles, such as: battery type, nominal capacity or useful capacity. Next, the storage capacity in second-life electric vehicles batteries available for each year between 2015 and 2020 has been calculated, as follows:

$$C_{SLBES} = \left(EV_{Registration} \cdot C_{Uselful}\right) \cdot 0.7$$

where C_{SLBES} is capacity of second-life electric vehicle battery energy storage systems in kWh, $EV_{Registration}$ is annual electric vehicle registrations and $C_{Uselful}$ is average useful capacity of electric vehicles in kWh. 0.7 expresses the useful capacity of second life batteries with respect to their nominal capacity in their first life

A series of hypotheses have been assumed in this study. On the one hand, the number of brands of electric vehicles registered in Tenerife can be more than 60 and the availability of datasheets for each of them is limited. For this reason, it has been assumed that the useful capacity and the battery type used in electric vehicles for year *X* will be equal to the useful capacity and the battery type used in the electric vehicle with the highest registration rate in that year.

Furthermore, it has been assumed that the battery used in an electric vehicle (first battery life), mostly lithium ion batteries, should be replaced when their capacity decreases to 70–80%, or approximately after 8-10 years, as reported in multiple sources [27][29][30][36][37][38][39][42]. Therefore, the batteries of electric vehicles registered between 2015 and 2020 will be available for a second life between 2025 and 2020.

On the other hand, it has been assumed that all electric vehicle batteries removed after reaching their first life will have a second life in stationary energy storage applications. The multiple external factors that may affect the use of second-life electric vehicle batteries have not been taken into account, such as: cost of reconditioning the used battery, warranty issues, social barriers, regulatory issues for the adoption of batteries, etc.

3.2.3. Electric vehicles registrations contribution model

Finally, the number of annual registrations of electric vehicles in the province of Santa Cruz de Tenerife from 2020 to 2030 has been foreseen, with the aim of reaffirming the growing participation of electric vehicles in the fleet of vehicles on the island of Tenerife. To carry out this last step, the same methodology described in the forecast of the annual wind generation in Tenerife carried out in the first study has been followed. In other words, the SARIMA model has been applied to our time series through Python's *auto_arima()* function. The results of this other model are shown in section 5.

3.3. Technical-economic feasibility a second-life electric vehicle battery energy storage systems in a wind farm

The project of technical and economic feasibility of the use of second-life battery energy storage system in a real wind farm has been carry out. For this, we have had the collaboration of the company DISA Renovables S.L., who has provided us with data on the generation of one of its wind farms located in the south of the island of Tenerife, ICOR Wind Farm. It is a wind farm that has 6 SG 3.4-132 wind turbines, which offer approximately 21 MW of wind power.

In this third study, three databases have been used:

- Database provided by DISA Renovables S.L. This database is based on data on the operation of the ICOR Wind Farm, which shows information on: status of the wind turbines, active power generated by each wind turbine, active power injected into the grid by the wind farm, power limitations by REE and meteorological data provided by the anemometers of each wind turbine. The period studied includes the following dates: 12/01/2018 - 06/30/2020.
- Database on the electricity market in the Canary Islands. This database has been obtained from REE, through the e-sios platform. The scheduling of generation in the Canary Islands is carried out based on an economic dispatch that takes into account the recognized costs of the generation groups, so that the energy demand is covered by those groups that suppose a lower cost for the system. The remuneration of the generation groups in non-peninsular systems is calculated based on variable costs (variable start-up, operation, reserve and operation and maintenance costs) and fixed costs (power guarantee), whose parameters are verified by the System Operator and recognized by the Ministry of Industry, Tourism and Energy. The aforementioned database offers information on the electricity pool price, costs for deviations, etc. The period studied is from 09/01/2015 to 05/31/2020.
- Database on meteorological data on the island of Tenerife. Specifically, the meteorological data have been downloaded at the site of the wind farm under study between 12/31/2017 and 07/01/2020, through the Dark Sky platform [43].

Firstly, the data has been cleaned and processed, as we have done so far with the previous databases used. Once the information has been filtered, a data science work has been carried out in order to obtain all the useful information possible. It has sought to have knowledge about the behaviour of electricity pool price on the island of Tenerife, the availability of wind resource in the municipality of Arico, and the operating characteristics of ICOR wind farm. The use of Python libraries such as *Pandas* and *Numpy* have been essential in the work carried out.

Secondly, the power curve of ICOR Wind Farm has been studied taking into account the operation data of ICOR Wind Farm and the meteorological data of site. In order to be more realistic in the analysis, a polynomial regression of the power data delivered by all the wind turbines has been carried out as a function of the available wind resource. This has allowed us to model the power curve of the wind farm under study, allowing us to predict what its behaviour will be under certain wind conditions. The polynomial adjustment carried out has been of the sixth degree. It has been verified how good the model obtained is through the coefficient of determination (R^2). All this has been carried out thanks to the Excel calculation tool.

Thirdly, we have focused on studying the feasibility of applying what has been researched so far. Two possible scenarios have been simulated. On the one hand, a baseline scenario has been generated, that is, without the use of any energy storage system. The power curve of the ICOR Wind Farm, the analysis carried out on the wind resource at the site under study and the power limitations established by REE to ICOR Wind Farm between 2018-2020 have been taken as a reference. The simulation has sought to estimate the amount of “wasted energy” due to power reductions by the Electric System Operator, REE. On the other hand, a second scenario has been simulated under the same conditions as the base scenario, but on this occasion a second-life electric vehicle battery energy storage system (BESS) has been included, in order to minimize the percentage of annual wasted energy due to the power limitations.

Sizing of energy storage system has been estimated by averaging daily wasted energy in the first scenario. However, since the power reductions do not follow any clear pattern, are difficult to predict and can be very abundant in a specific month and non-existent in others, a sensitivity analysis of the model has been carried out in the face of the modification of the dimensioning of the storage system. In this way, the necessary second-life battery energy storage system has been dimensioned, without oversizing it. It should be said that, according to the study carried out previously, the limitations regarding the energy storage capacity in second-life batteries have been taken into account, as well as their lower efficiency. An efficiency around 85% has been considered, according to what has been studied so far. Additionally, a calculation of CO_2 emissions savings that the installation of a second-life battery energy storage system would entail has been made, based on the amount of energy that can be injected into the grid from the batteries, taking into account the CO_2 emission factor (0.776 kg CO_2/KWh) published by the Institute for Diversification and Saving of Energy (IDAE, for its acronyms in Spanish) [44].

Finally, an economic study of the proposal has been carried out, taking into account the results obtained in the second scenario. For this, a series of specifications and hypotheses have been taken into account. Among the specifications are: the useful capacity of the energy storage system used, the annual energy production of ICOR Wind Farm, the income obtained due to the injection of energy into the grid from the batteries or the opportunity cost/discount rate used in the study, taking into account the recommendations of the CNMV [45]. These values will be shown and discussed in more detail in section 6. On the other hand, the hypotheses considered have been the following: the useful life of second-life batteries, which has been established at 10 years; the price of reconditioning removed electric vehicle batteries for a second life, which has been estimated by [16] to be about 55€/kWh in 2025; the annual costs associated with the operation and maintenance of the batteries have been set at around 100€/year; the increase in the income (around 5%); the CPI (1%); and, tax rate (20%).

It is important to highlight that the storage capacity in second-life batteries in Tenerife has been estimated for the years between 2050-2030, so the study has been carried out as an estimate for the year 2025. For this reason, an annual increase of 5% has been considered in the income obtained from the energy injected from the batteries into the grid, either due to an increase in the electricity pool or an increase in the slogans established by REE. This second reason is very likely, since the increase of renewable energy in the grid is increasing, which will make the power reduction occur more frequently. There is still a long way to go until the necessary innovation is produced in the electricity grid, in a way that allows the integration of large amounts of renewable energy without affecting the energy security of the island's electricity system.

The fundamental problem in any investment decision is to determine the profitability of the project, to assess/decide whether or not to carry it out, and thus have a measure that allows ranking the existing investment options or alternatives based on their profitability and thus select the most convenient. To assess the economic viability of the project, a series of dynamic indicators have been used, that is, methods that take into account the time value of money, homogenize the amounts received at different moments of time through updating or discount procedures. These are:

- Net Present Value (NPV): It is defined as the difference between the present value of the cash inflows generated by the project and the value of the initial investment.
- Internal Rate of Return (IRR): It is the discount rate that makes the investment coincide with the present value of future cash flows.
- Payback period or discounted payback: It is the period of time (number of years) that is needed for the updated value of the net cash flows generated up to that moment to be equal to the initial investment.

As APPENDIX II, the Python (.py) and Excel (.xlsx) files with all the calculations performed in the study will be attached.

4. The role of wind energy in Tenerife

In this section, the current energy mix of Tenerife, the role that wind energy plays in the structure of electricity generation and the expected evolution in the integration of wind energy in the island's electricity grid by the year 2030 have been studied in depth.

Table 1 shows a general analysis of the demand and the generation structure of the Tenerife power system between 2015 and 2020. 284,548 data have been analyzed for each variable under study. From this analysis we can see that the electricity demand in Tenerife during the period studied ranges from 0-571.9MW, with an average of 396.5MW. The generation technology that has the greatest participation in the power system is combined cycle, injecting up to 396MW into the grid and with an average of 178.1MW. However, the technology with the lowest participation on average is the gas turbine, with an average of 15.1MW, although with a maximum of 206.5MW, due to the power ramps imposed on the grid by variable renewable technologies, such as wind and photovoltaic or due to some incident on the grid.

On the other hand, the renewable technologies present in Tenerife's power system, that is, wind and solar photovoltaic, have an average of 21.9MW and 20.8MW of power injection into the grid respectively. A maximum of 181.9MW of wind power has been detected on the grid and a maximum of 100.3MW of photovoltaic power. This figures are well above the maximum of 45.6MW of power generated by diesel engines on the grid.

Table 1. Analysis of electricity demand (MW) and generation structure (MW) of Tenerife's power system between 2015 and 2020.

	Real Demand	**Programmed Demand**	**Projected Demand**	**Combined Cycle**	**Diesel Engines**	**Gas Turbine**	**Steam Turbine**	**Wind**	**Photovoltaic**
Count	284,548	284,548	284,548	284,548	284,548	284,548	284,548	284,548	284,548
Mean	396.5	396.3	396.6	178.1	28.4	15.1	131.2	21.9	20.8
Std	80.4	81.4	80.4	45.2	11.3	22.2	45.6	34.1	29.0
Min	0	0	0	0	0	0	0	0	0
25%	317.6	317.4	318.6	149.7	18.4	0	96.1	1.6	0
50%	414.8	415.2	415.7	172	34.4	0	130.8	8.9	0
75%	464.9	465.4	465.1	197.3	36.3	24	173.6	23.8	41.5
Max	574.9	587.8	580.4	396	45.6	206.5	213	181.9	100.3

Table 2 shows the installed power (MW) in each municipality of Tenerife by technology. This study shows how centralized the generation is on the island, since approximately 75% of the generation is concentrated in the south of it. Specifically, 767.48MW are available in the municipality of Granadilla de Abona and 215.43MW in the municipality of Arico, out of a total of 1,302MW installed in Tenerife.

On the other hand, the island has a wide portfolio of technologies to meet its electricity demand. However, a large part of the generation depends on conventional sources based on the use of fossil fuels. Fuel-Gas/Combined Cycle/Carbon plants have 959.11MW installed (73.66%), while photovoltaic plants account for 105.97MW (8.14%) and wind farms 195.92MW (15.05%). There are also two cogeneration/waste/biomass plants, which have 39.80MW installed between them (3.06%), and small hydraulic installations, with 1.22MW installed (0.09%). In short, there is still a long way to go for low carbon energy sources to dominate generation on the island of Tenerife.

Table 2. Power installed by technology (MW) in Tenerife.

Municipality	Photovoltaic	Hydraulic	Cogeneration/Waste /Biomass	Wind	Fuel-Gas/Combined Cycle/Carbon	TOTAL (MW)
S/C de Tenerife	3.274	0	38.2	0	0	41.474
San Cristobal de La Laguna	0.339	0	0	0	0	0.339
El Rosario	0.564	0	0	0	0	0.564
Candelaria	0.09	0	0	0	179.47	179.56
Arafo	0.912	0	0	0	0	0.912
Guimar	2.434	0	0	0	0	2.434
Fasnia	0.283	0	0	0	0	0.283
Arico	67.613	0	1.6	146.215	0	215.428
Granadilla de Abona	26.24	0	0	47.9	693.34	767.48
San Miguel de Abona	1.371	0	0	0	0	1.371
Arona	0.591	0	0	0	43.2	43.791
Adeje	0.971	0	0	0	0	0.971
Guia de Isora	0.193	0	0	0	43.1	43.293
Santiago del Teide	0.046	0	0	0	0	0.046
Buenavista del Norte	0.03	0	0	1.8	0	1.83
Los Silos	0.002	0	0	0	0	0.002
Icod de los Vinos	0.02	0.76	0	0	0	0.777
La Guancha	0.036	0.46	0	0	0	0.499
Los realejos	0.178	0	0	0	0	0.178
La Orotava	0.335	0	0	0	0	0.335
Pueeto de la Cruz	0.103	0	0	0	0	0.103
La Matanza de Acentejo	0.057	0	0	0	0	0.057
El Sauzal	0.064	0	0	0	0	0.064
Tacoronte	0.218	0	0	0	0	0.218
TENERIFE (TOTAL)	**105.97**	**1.22**	**39.80**	**195.92**	**959.11**	**1,302.01**
TENERIFE (%)	**8.14%**	**0.09%**	**3.06%**	**15.05%**	**73.66%**	**100%**

Figure 3 shows the average load curve of the Tenerife power system between 2015 and 2020. It can be seen how the hours of greatest demand on the island are between 20:00 and 21:00, while the hours of less power consumption occurs between 3:00 and 4:00 hours. In addition, in this graph, which summarizes the generation structure over the last 5 years, it is possible to confirm the great presence that conventional technologies have had and still have in the island's energy mix, especially technologies based on in the combined cycle and steam turbine.

However, in order to observe the behavior of the average load curve in the last year and to be able to analyze the changes in relation to the average load curve of the Tenerife's power system during the entire period under study (2015-2020), Figure 4 shows the average load curve of the Tenerife power system in 2019. On this occasion, a greater share of wind energy and a decrease in generation based on the combined cycle can be seen. The share of the rest of technology remains practically the same.

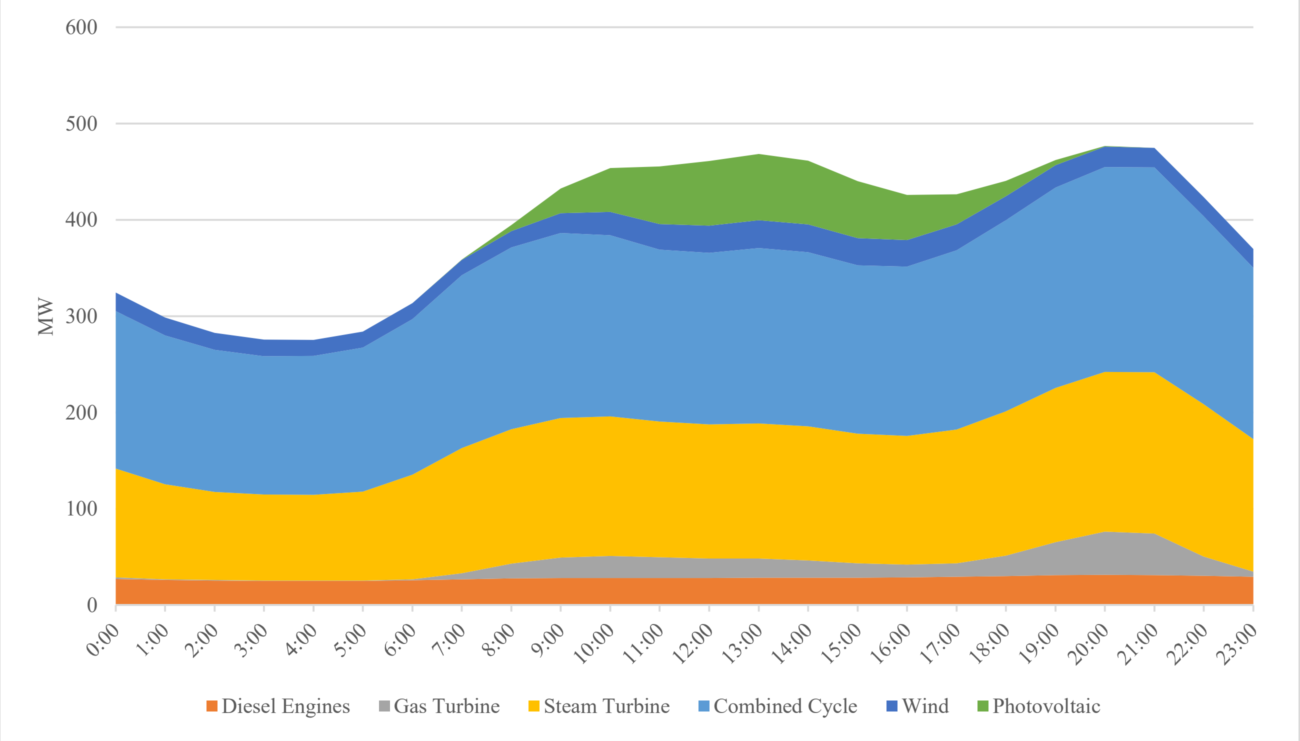

Figure 3. Average load curve for the Tenerife's power system (2015-2020).

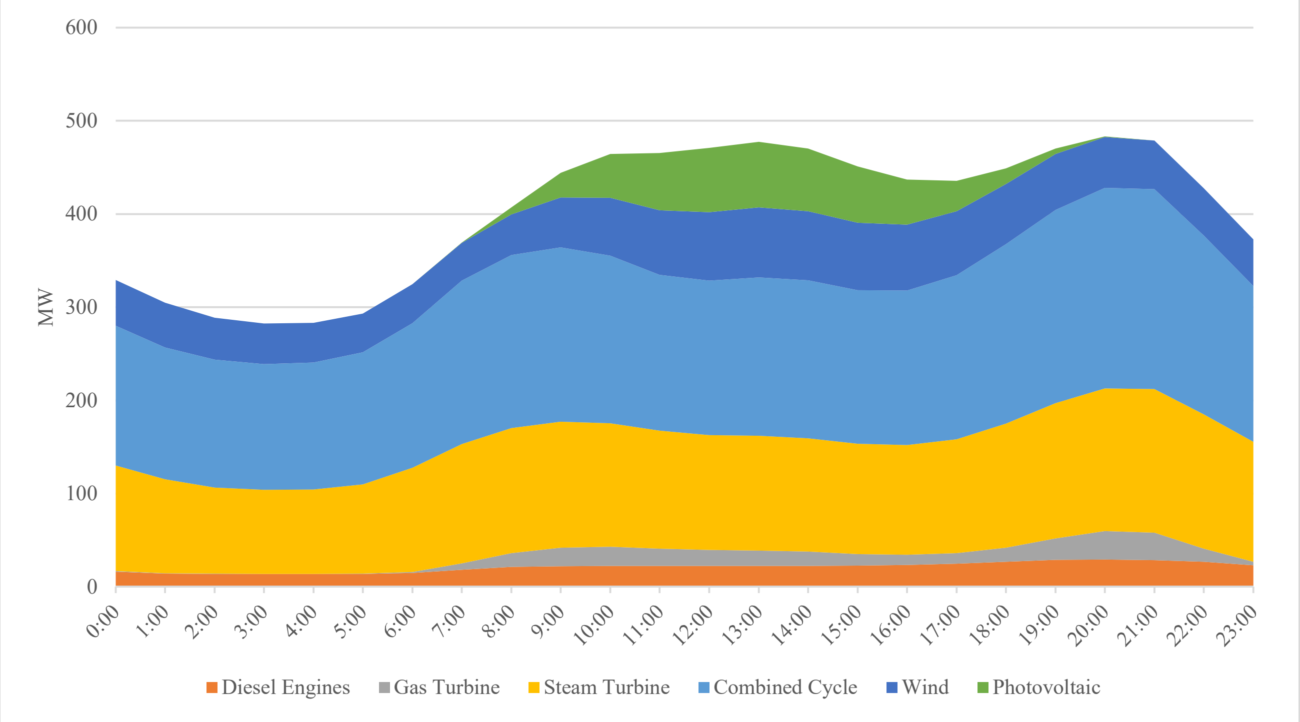

Figure 4. 2019 average load curve for the Tenerife's power system.

Focusing on the role of wind energy on the island of Tenerife, Figure 5 shows the distribution of wind power installed on the island of Tenerife. Specifically, the installed wind power (195.92MW) is distributed among three municipalities: Arico, Granadilla de Abona and Buenavista del Norte.

Table 3 breaks down the different wind farms on the island under study, as well as their location and installed power. In this case, the municipality with the highest installed wind power is Arico, with 146.215MW. On the other hand, the wind farms with the highest power are: The Icor Wind Farm, located in Arico, with an installed power of 20.79MW; The Poris de Abona Wind Farm, located in Arico, with an installed capacity of 19.6MW; The Arico Environmental Complex Wind Farm, also located in Arico, with an installed capacity of 18.4MW; The La Roca Wind Farm. located in Granadilla de Abona, also with a power of 18.4MW; and the Chimiche II Wind Farm, located in Arico, with an installed capacity of 18.375MW.

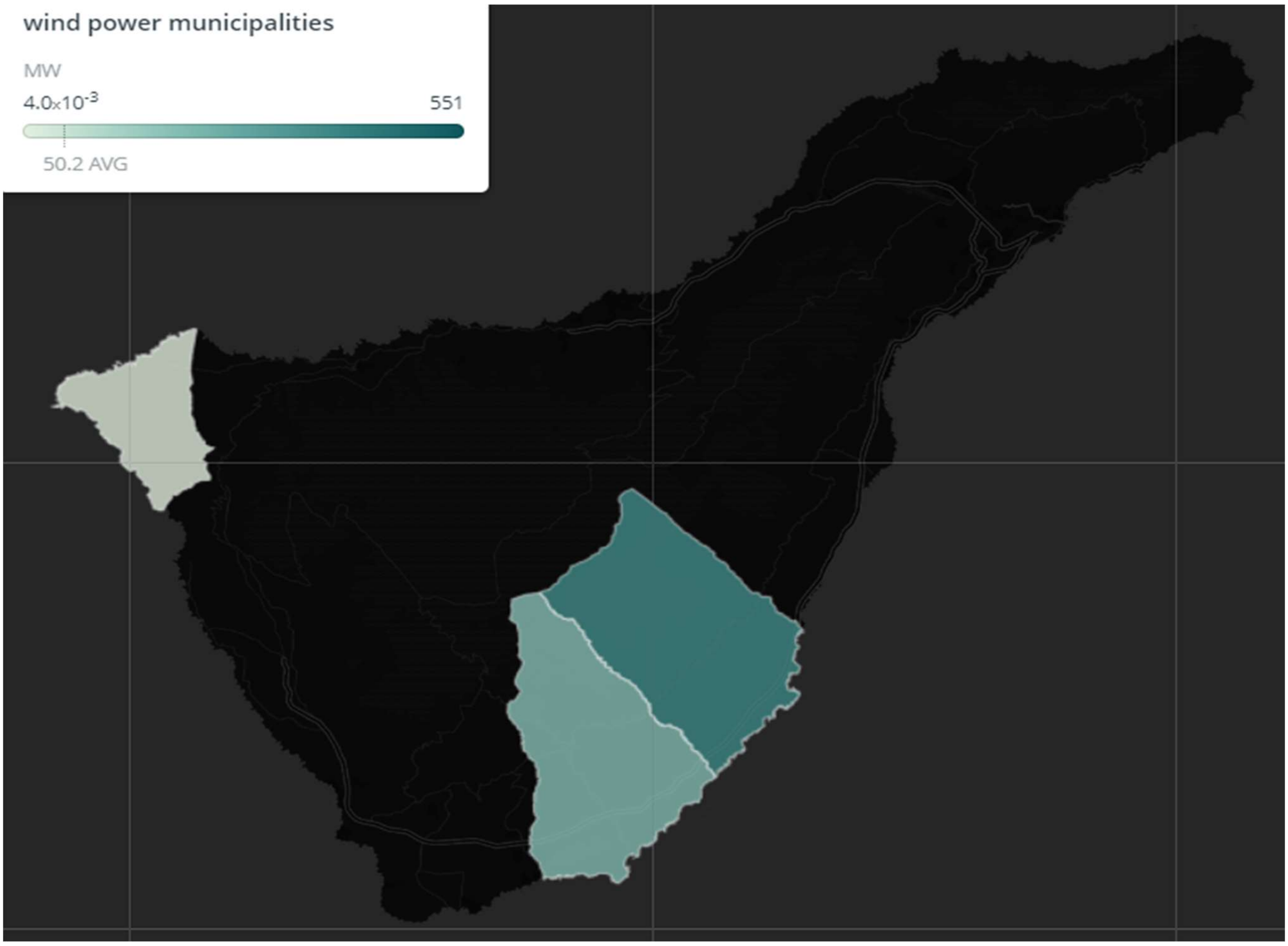

Figure 5. Wind power installed by municipalities in Tenerife. Source: REE

Table 3. Wind power installed by municipalities in Tenerife.

Municipality	Wind Farm Name	Installed Power (MW)	TOTAL (MW)
Arico	PARQUE EOLICO ICOR	20.79	146.215
	PARQUE EOLICO BERMEJO	12.6	
	PARQUE EOLICO ABOTE	10.5	
	P.E. DE ARICO	16.5	
	P.E. LLANOS DE LA ESQUINA	5.95	
	PARQUE EOLICO TAGORO RISCO BLANCO	16.45	
	P.E. LA MORA	7.05	
	PARQUE EOLICO PORIS DE ABONA	19.6	
	PARQUE EOLICO COMPLEJO MEDIOAMBIENTAL DE ARICO	18.4	
	PARQUE EOLICO CHIMICHE II	18.375	
Granadilla de Abona	PARQUE EOLICO ARETE	16.8	47.9
	PARQUE EOLICO LA ROCA	18.4	
	PARQUE EOLICO GRANADILLA DE ABONA I	0.45	
	P.E. GRANADILLA III	4.8	
	P.E. GRANADILLA II	5.5	
	P.E.GRANADILLA	1.95	
Buenavista del Norte	P.E. PUNTA DE TENO	1.8	1.8

Table 4 shows an analysis of the injection of wind power into the grid between 2015-2020. Previously, we already mentioned that during the period under study, wind power generation on the grid represented an average of 21.9MW, and highs of up to 181.9MW had been recorded. Here we can see a more detailed analysis of the participation of wind technologies in the power system of Tenerife. Specifically, there is an increase in wind power in the grid, going from an average of 8.2MW in 2015 to 56.1MW in 2019. The largest increase in wind power injected into the grid is observed between 2018 and 2019, going from an average of 17.2MW to 56.1MW, as already mentioned. In fact, the highest peak of wind power into the grid (181.9MW) has been detected in the last year. It should be said that the data collected in 2020 are not entirely conclusive, since only the data corresponding to the first 5 months of this year have been analyzed. However, everything indicates that wind power will remain at 2019 levels and will even grow. In fact, it was detected that at 00:40 on March 6, 2020, wind power covered 54.78% (177MW) of the electricity demand on the island of Tenerife (323.1MW).

Table 4. Analysis of the wind power injected (MW) into the grid.

	2015-2020	2015	2016	2017	2018	2019	may-20
Count	284,548	52,533	52,685	52,540	52,475	52,413	21,877
Mean	21.9	8.2	7.8	9.6	18.0	56.1	44.8
Std	34.1	8.3	7.9	10.5	17.2	53.2	49.2
Min	0	0	0	0	0	0	0
25%	1.6	0.8	1.1	1	2.3	5.9	4
50%	8.9	5.2	4.8	5.4	12.8	40.1	22.4
75%	23.8	14.5	13.4	16.3	31.9	100.8	77.1
Max	181.9	33.5	32.1	55.4	110.5	181.9	181

So far we have talked in terms of power, it is convenient to do an analysis in terms of energy. In Figure 6 you can see the evolution of the annual electricity demand and the annual generation by technology in MWh. A slight increase in electricity demand can be observed, going from an annual energy consumption of 3,407,291MWh in 2015 to an annual demand of 3,534,502MWh in 2019.

Regarding the annual energy generation, it can be observed how combined cycles and steam turbines dominate production. In this sense, it should be noted that the annual energy generation through combined cycles has decreased from 1,610,114MWh in 2015 to 1,493,723MWh in 2019. On the other hand, in terms of renewable generation, annual photovoltaic energy remains practically constant, with values of around 180,000MWh per year. And, annual wind energy has undergone significant changes, going from 71,915MWh in 2015 to 491,156MWh in 2019. Figure 7 shows more clearly the increase in annual wind energy generation on the island of Tenerife, going from 3% of 2015 total generation (3.41TWh) to 14% of 2019 total generation (3.53TWh). Obviously, self-consumption has not been considered in this study.

Figure 8 shows the evolution of monthly wind power generation between 2015 and 2020, as well as a study of its trend, through indicators such as the annual average of monthly wind power generation or the moving average of analysed time series. It can be seen how the annual average of monthly wind power generation in Tenerife has suffered a significant increase in the last 5 years, especially in 2018 and 2019. It has gone from a monthly average of 5,993MWh in 2015 to 40,930MWh in 2019. This growing trend in wind power generation can be confirmed if we analyse the moving average of monthly wind power generation data in Tenerife. This indicator has allowed us to smooth the graph and eliminate the noise produced by the intermittency of wind resource, giving us a clearer view of the trend of wind generation in the period under study.

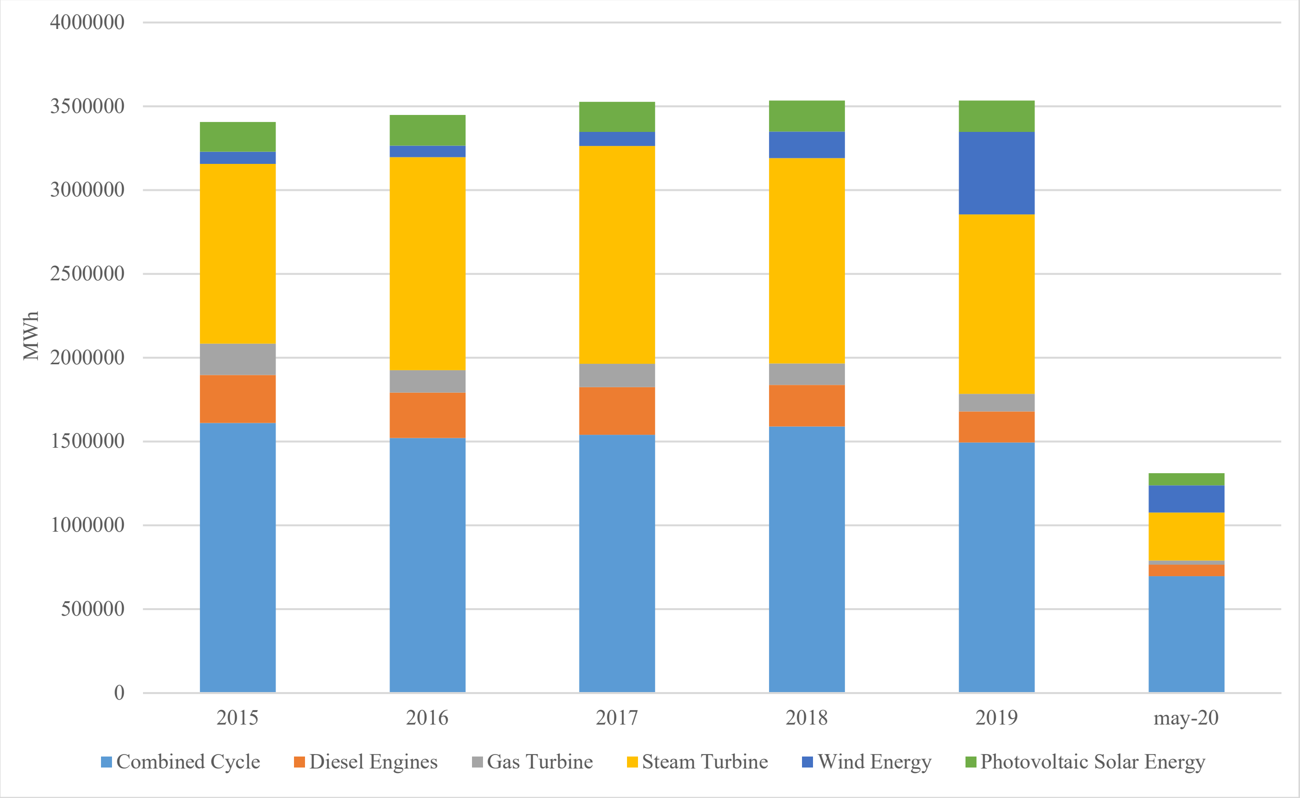

Figure 6. Evolution of annual energy generation (MWh) by technology between 2015 and 2020.

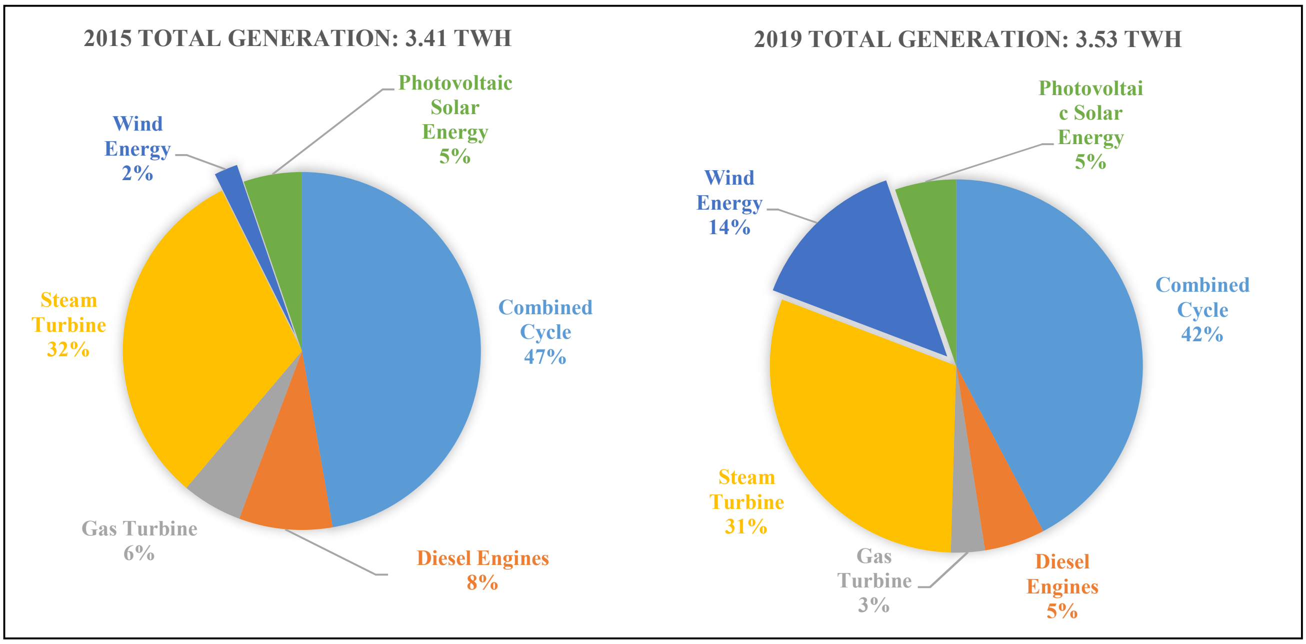

Figure 7. Comparison of annual energy generation (%) by technology between 2015 and 2020.

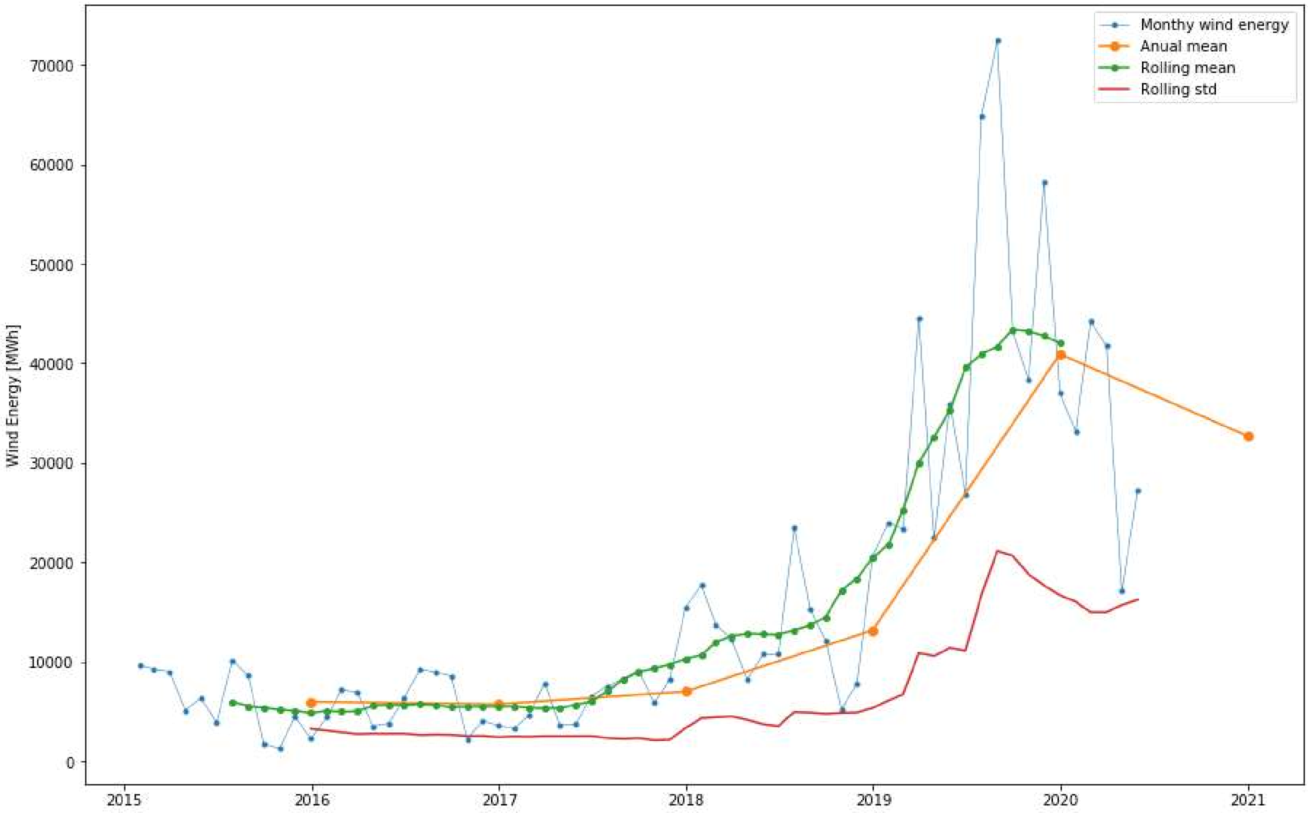

Figure 8. Monthly wind energy generation trend between 2015 and 2020.

Annual wind energy generation has been planned in Tenerife from 2020 to 2030, with the aim of studying the evolution of the participation of this type of energy in the island's electrical system in the future. According to the prediction obtained in wind energy contribution model explained in section 3 (Figure 9), it is expected that the participation in energy generation in Tenerife's electricity system will continue to increase over time, to the point of contributing approximately 1,150,000MWh per year. This projection considers that investment will continue to be made in wind energy projects on the island, as has been done in the last two years, 2018 and 2019. It should be noted that the predictions made here are merely illustrative, since in order to make a reliable prediction, others variables, such as the influence of the global pandemic due to COVID-19, wind power auctions to come in Tenerife or electricity demand, should be taken into account. This would take a more extensive and complete work than that carried out in this study.

However, these projections may not be very far from reality, since in the Canary Islands much support and importance is being given to the decarburization of the electricity sector and the promotion of renewable energies. It is worth mentioning that the future installation of a new wind farm in Tenerife has already been approved. Specifically, one of the approved decrees refers to the Hoya de Lucas Wind Farm, promoted by Disa Eólica S.L.U. in the municipality of Arico and which has a total power of 19.2 MW.

On the other hand, it should not be forgotten that offshore wind energy is booming and the Canary Islands may be the perfect place to exploit this type of technology. The Canary Islands Oceanic Platform (Plocan) located on the horizon of the coast of Telde, Gran Canaria, Spain, is called to turn the islands into one of the few places in the world where to test all kinds of marine technologies. In fact, a prototype from the Andalusian company EnerOcean uses Plocan to test the world's first floating wind turbine with two turbines supported on the same structure, suitable for locations far from the coast and with greater depths, where it is impossible to cement the windmill tower on the seabed. Other companies such as GREENALIA, a company based in Galicia, Spain, will promote its first floating offshore wind installation in Gran Canaria, for which it has already started its processing. It is the GOFIO 50 MW wind farm located in the Southeast of the Island of Gran Canaria, in front of the municipality of San Bartolomé de Tirajana and very close to the port of Arinaga. It will involve an investment of more than 130 million Euros.

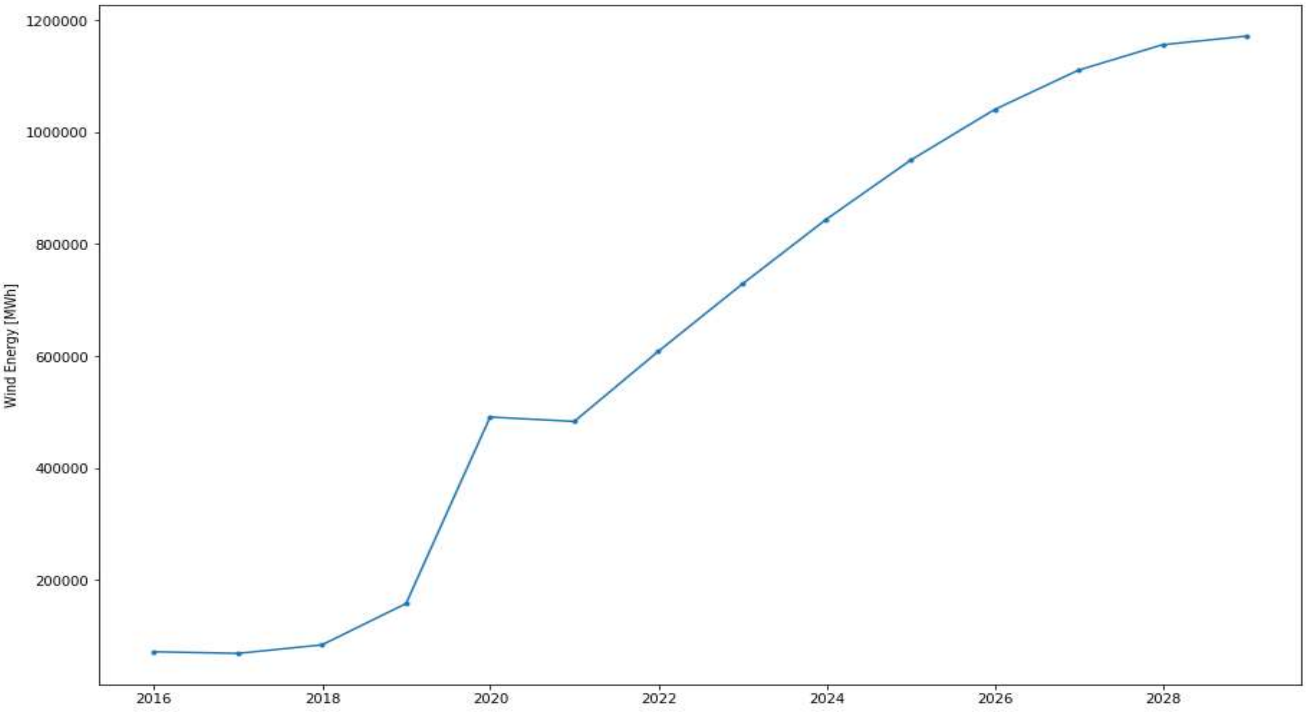

Figure 9. Forecast of the annual wind energy generation from 2020 to 2030

5. Evolution of electric mobility in Tenerife

In this fifth section, electric mobility on the island of Tenerife has been studied. In particular, the evolution of electric vehicle fleet in the last decade has been studied, as well as its growth over time, in order to observe the potential and feasibility of use of second-life electric batteries as battery energy storage system in a future scenario.

Table 5 summarizes the evolution of the vehicle fleet in Tenerife between 2010 and 2020. The vehicle fleet has increased from 768,924 vehicles in 2010 to 881,226 in 2020. Almost all the vehicles in Tenerife use gasoline or diesel as fuel. In 2020, gasoline vehicles represent 70.2% (595,553 vehicles) of the fleet and diesel vehicles 28.9% (277,504 vehicles).

On the other hand, electric vehicles only represent 0.13% (1,159 vehicles) of 2020 vehicle fleet. However, the fleet of electric vehicles is the one that has grown the most. Electric vehicles have gone from being 83 in 2010 to 305 in 2015 and 1,159 in 2020. This is summarized in an increase of 267% between 2010 and 2015, and an increase of 280% between 2015 and 2020. This confirms the trend growing that electric mobility has suffered in recent years (Table 6). Figure 10 shows the increase in the electric vehicle fleet between 2010 and 2020.

Table 5. Evolution of fleet of vehicles by fuel (2010-2020).

	Fleet of vehicles	Electric	Diesel	Gasoline	Liquefied petroleum gas	Others fuels	Unspecified
2010	768,924	83	222,566	539,928	0	23	6,324
2015	782,372	305	244,308	532,071	121	32	5,535
may-20	881,226	1,159	277,504	595,553	761	39	6,210

Table 6. Increase in the electric vehicle fleet between 2010 and 2020.

	2010 - 2015	2015 - 2020
Fleet of electric vehicles	267.47%	280%
Fleet of diesel vehicles	9.77%	13.59%
Fleet of gasoline vehicles	-1.46%	11.93%

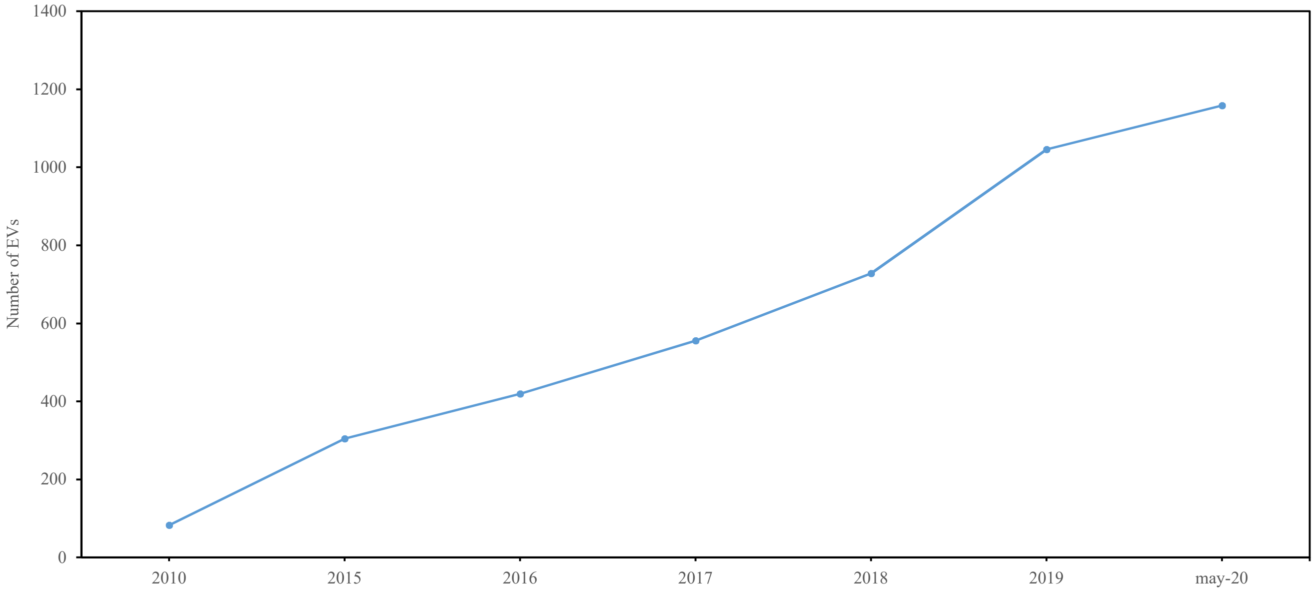

Figure 10. Fleet of electric vehicles evolution between 2015 and 2020.

Figure 11 shows in detail the fleet of electric vehicles by vehicle type in the years 2010, 2015 and 2020. In 2020, the electric vehicle fleet is made up of: 1 bus, 14 trucks up to 3500kg, 107 mopeds, 77 vans, 196 motorcycles, 656 passenger cars and 108 other type of vehicles. Therefore, 2020 electric vehicle fleet is dominated by passenger cars and motorcycles.

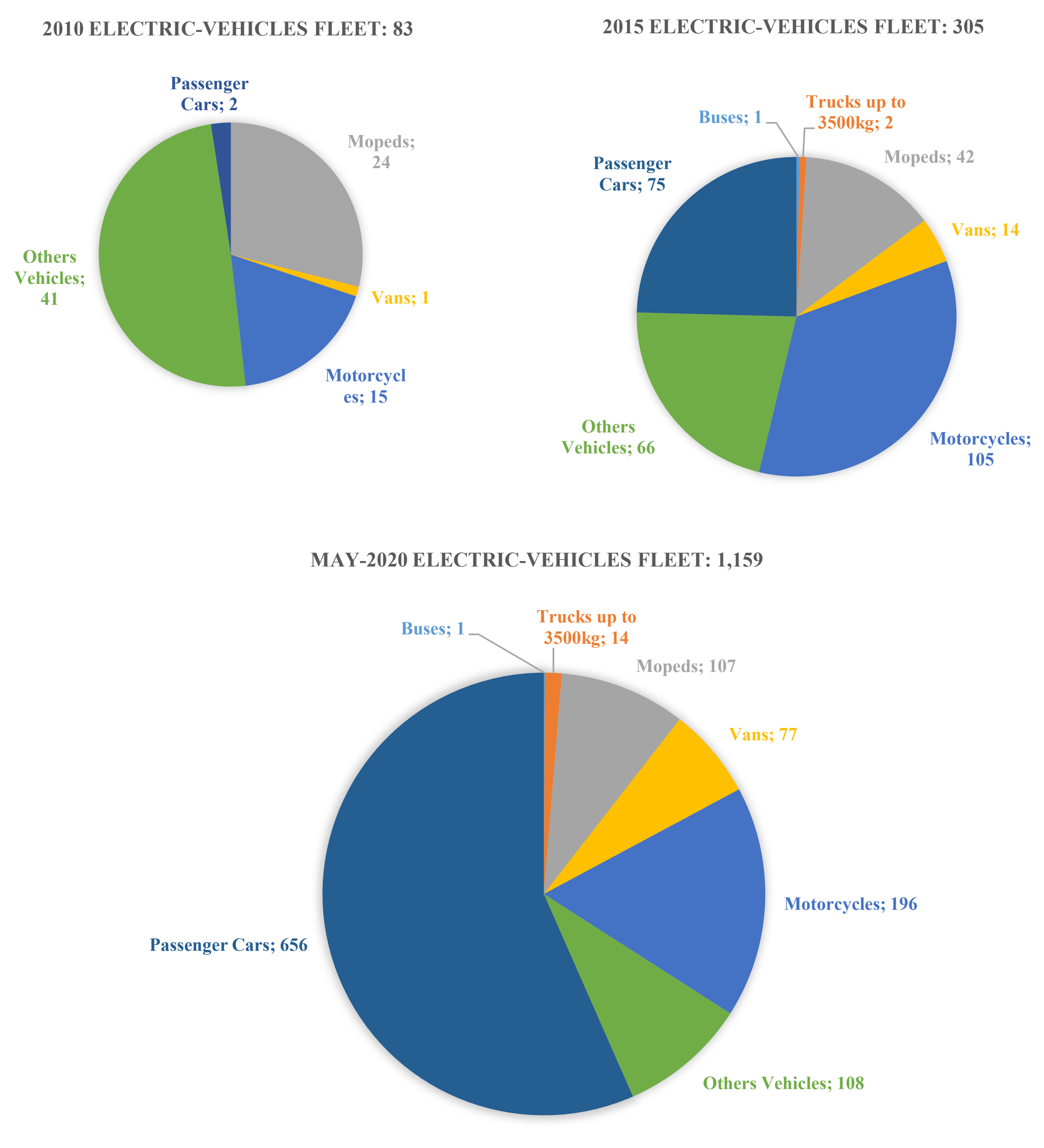

Figure 11. Fleet of electric vehicles evolution by vehicle type between 2010 and 2020.

After analysing the fleet of vehicles in Tenerife, we have proceeded to study the registrations of electric vehicles in the last 5 years.

- 2015 total vehicle registrations in the province of Santa Cruz de Tenerife was 27,165 and total electric vehicle registrations was 64. Thus, 2015 total electric vehicle registrations in the province of Santa Cruz de Tenerife represented 0.24% of total vehicle registrations.
- 2016 total vehicle registrations in the province of Santa Cruz de Tenerife was 32,915 and total electric vehicle registrations was 100. Thus, 2016 total electric vehicle registrations in the province of Santa Cruz de Tenerife represented 0.30% of total vehicle registrations.
- 2017 total vehicle registrations in the province of Santa Cruz de Tenerife was 35,895 and total electric vehicle registrations was 135. Thus, 2017 total electric vehicle registrations in the province of Santa Cruz de Tenerife represented 0.38% of total vehicle registrations.
- 2018 total vehicle registrations in the province of Santa Cruz de Tenerife was 37,276 and total electric vehicle registrations was 173. Thus, 2018 total electric vehicle registrations in the province of Santa Cruz de Tenerife represented 0.17%.
- 2019 total vehicle registrations in the province of Santa Cruz de Tenerife was 36,139 and total electric vehicle registrations was 263. Thus, 2019 total electric vehicle registrations in the province of Santa Cruz de Tenerife represented 0.73%.
- The number of registrations in the province of Santa Cruz de Tenerife during 2020, so far, is 6454 and the number of registrations of electric vehicles is 108, which represents 1.67% of the total registrations until May 2020.

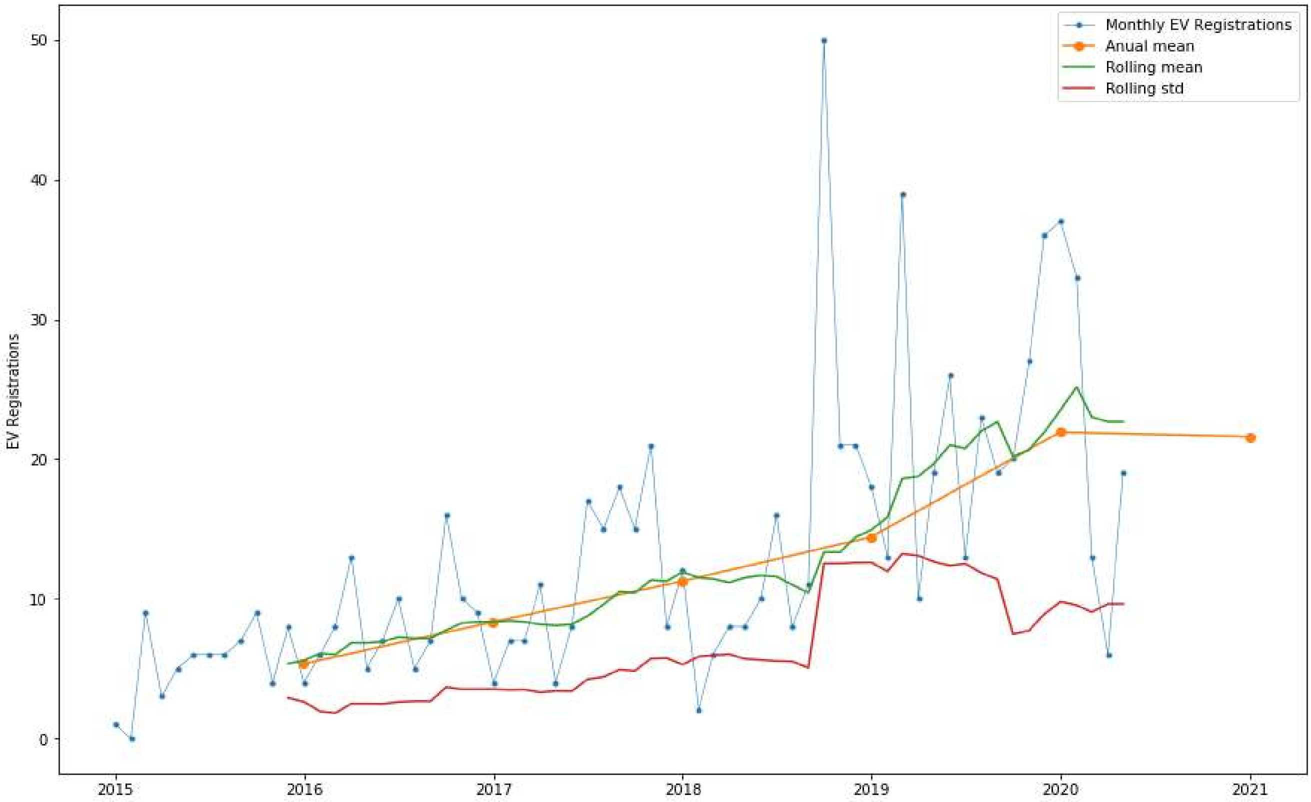

Figure 12. Monthly electric vehicle registrations trend between 2015 and 2020.

Figure 12 shows the evolution of monthly electric vehicles registrations in the province of Santa Cruz de Tenerife between 2015 and 2020, as well as a study of its trend, through indicators such as the annual average of monthly electric vehicle registrations or the moving average of analysed time series. It can be seen how the annual average of monthly electric vehicles registration in Tenerife has suffered an increase in the last 5 years. It has gone from a monthly average of 5.3 registered vehicles in 2015 to 21.9 registered vehicles in 2019. In addition, the monthly average of electric vehicles so far in 2020 is 21.6, which is to say that the increase in electric vehicle registrations per year will continue to increase. This growing trend in electric vehicles registrations can be confirmed if we analyse the moving average of data. This indicator has allowed us to smooth the graph, giving us a clearer view of the trend of electric registration in the period under study.

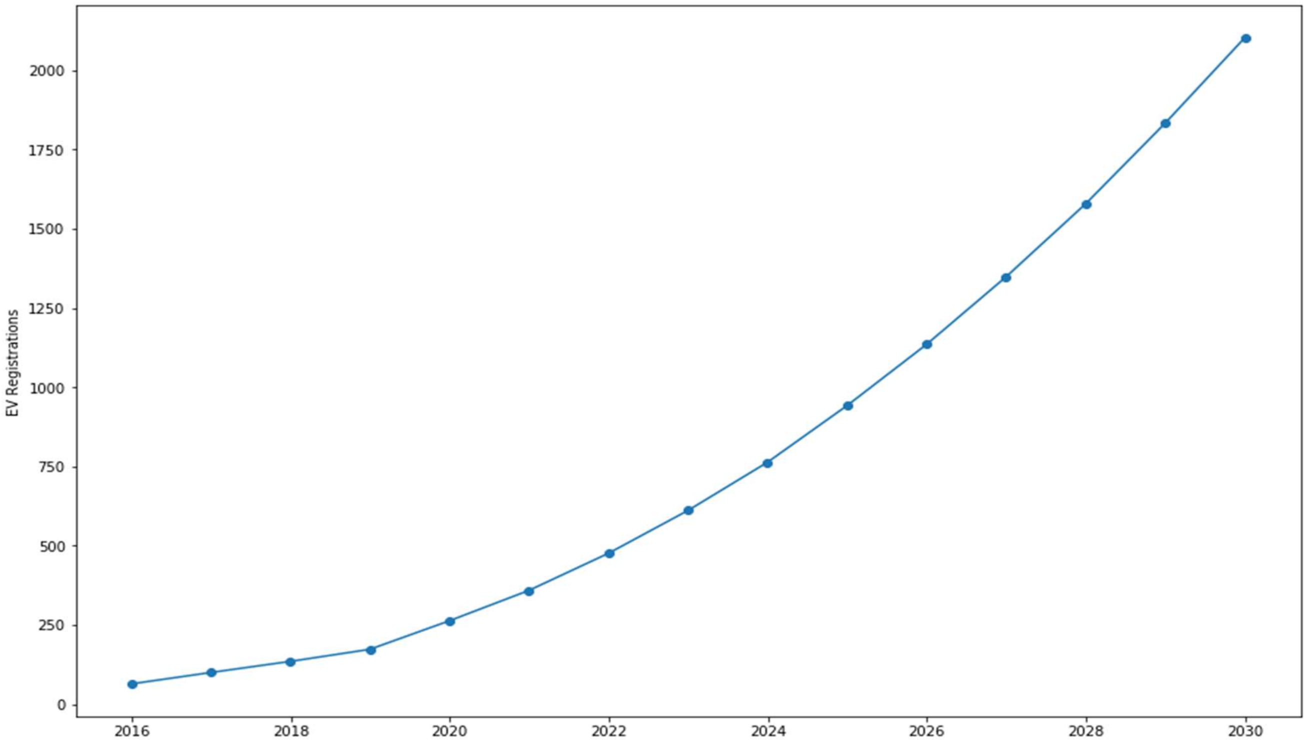

Figure 13. Forecast of the annual electric vehicle registrations from 2020 to 2030.

Total annual registrations of electric vehicles in the province of Santa Cruz de Tenerife from 2020 to 2030 has been foreseen, with the aim of reaffirming the growing number of electric vehicles in the fleet of vehicles on the island of Tenerife. Figure 13 shows the forecast obtained for the annual registrations of electric vehicles in the province of Santa Cruz de Tenerife in the following decade, until 2030. It is observed how the annual registrations of electric vehicles grow exponentially in Tenerife, anticipating the annual registration of more than 2,000 electric vehicles by 2030, that is, approximately 10 times higher than the number of registrations produced in 2019, according to our Electric vehicles contribution model explained in section 3.

In this sense, it is important to mention that the Council of Ministers in Spain has approved in June 2020 a Royal Decree that articulates the second edition of the Efficient and Sustainable Mobility Incentive Program (*Moves*), which has an endowment budget of 100 million Euros and that will give aid to the purchase of electric vehicles of up to 5,500 Euros, to which will be added an additional 1,000 Euros contributed by the manufacturers. It is expected that this type of program will help to comply with the forecasts set out, so that the dominance of the electric vehicle in the fleet of vehicles on the island of Tenerife is increasingly a reality.

Table 7. Analysis of annual electric vehicle registrations (2015-2020).

2015 Total EV Registrations		64
Municipality *(with most registrations)*	SC TENERIFE	18
Vehicle Brand *(with most registrations)*	RENAULT	21
Vehicle Model *(with most registrations)*	ZOE	11
Vehicle Type *(with most registrations)*	Passenger Car	35
EV Category *(with most registrations)*	BEV	30
Service *(predominant)*	B00 - Private - Unspecified	59
2016 Total EV Registrations		100
Municipality *(with most registrations)*	SC TENERIFE	23
Vehicle Brand *(with most registrations)*	NISSAN	20
Vehicle Model *(with most registrations)*	I3/NISSAN LEAF 30KWH	8(x2)
Vehicle Type *(with most registrations)*	Passenger Car	52
EV Category *(with most registrations)*	BEV	41
Service *(predominant)*	B00 - Private - Unspecified	76
2017 Total EV Registrations		135
Municipality *(with most registrations)*	SC TENERIFE	48
Vehicle Brand *(with most registrations)*	BMW	20
Vehicle Model *(with most registrations)*	I3/OUTLANDER PHEV KAITEKI	14(x2)
Vehicle Type *(with most registrations)*	Passenger Car	101
EV Category *(with most registrations)*	BEV	69
Service *(predominant)*	B00 - Private - Unspecified	122
2018 Total EV Registrations		179
Municipality *(with most registrations)*	SAN MIGUEL	41
Vehicle Brand *(with most registrations)*	CITROEN/NISSAN	29
Vehicle Model *(with most registrations)*	BERLINGO/NISSAN LEAF 40KWH	29/25
Vehicle Type *(with most registrations)*	Passenger Car	112
EV Category *(with most registrations)*	BEV	110
Service *(predominant)*	B00 - Private - Unspecified	158
2019 Total EV Registrations		263
Municipality *(with most registrations)*	LA LAGUNA	80
Vehicle Brand *(with most registrations)*	HYUNDAI	55
Vehicle Model *(with most registrations)*	KONA, KAUAI	46
Vehicle Type *(with most registrations)*	Passenger Car	193
EV Category *(with most registrations)*	BEV	218
Service *(predominant)*	B00 - Private - Unspecified	207
2020 EV Registrations		108
Municipality *(with most registrations)*	S C TENERIFE	43
Vehicle Brand *(with most registrations)*	NISSAN	23
Vehicle Model *(with most registrations)*	NISSAN LEAF 40KWH	17
Vehicle Type *(with most registrations)*	Passenger Car	81
EV Category *(with most registrations)*	BEV	105
Service *(predominant)*	B00 - Private - Unspecified	90

Table 8. Estimation of available second-life electric vehicle battery energy storage capacity between the years 2025-2030.

Year	Vehicle Model (Higher Registration)	Battery Type	Battery Capacity (KWh)	Useful Battery Capacity (KWh)	Total EV Registration	Second-life EV BES (KWh)
2015	ZOE	Lithium-ion	25	22	64	985.6
2016	I3/NISSAN LEAF 30KWH	Lithium-ion	30	27.2	100	1904
2017	I3	Lithium-ion	30	27.2	135	2,570.4
2018	NISSAN LEAF 40KWH	Lithium-ion	40	39.2	179	4,911.76
2019	KONA, KAUAI	Lithium-ion	40	39.2	263	7,216.72
may-20	NISSAN LEAF 40KWH	Lithium-ion	40	39.2	108	2,963.52

Table 7 shows a summary of the analysis of the annual registrations of electric vehicles between 2015 and 2020. In this study, it has obtained very useful information for the research carried out. Specifically, which municipalities in the province of Santa Cruz de Tenerife have a higher registration rate for electric propulsion vehicles by year, which are the model and brand of vehicle with higher registration rates for electric vehicles by year, which are the vehicle type with higher registration rates for electric vehicles by year, which are the electric vehicle category with higher registration rates for electric vehicles by year and which are the service with higher registration rates for electric vehicles in the province of Santa Cruz de Tenerife by year. In 2019, municipality of province of Santa Cruz de Tenerife with the highest number of registrations of electric vehicles was La Laguna, vehicle model was NISSAN, vehicle brand was NISSAN LEAF, vehicle type was passenger car, electric vehicle category was Battery Electric Vehicle (BEV) and the predominant service was private.

Forecasting of availability of batteries removed from electric vehicles on the island of Tenerife by year has carry out and the capacity of second-life electric vehicle batteries that will be available in the next decade has estimated. After conducting the study of technical sheets of vehicle brands of electric vehicles with a higher registration rate and the research of characteristics of the batteries used in these vehicles, it has been possible to estimate the available second-life electric vehicle battery energy storage capacity between the years 2025-2030. Table 8 summarizes the results obtained. It should be noted that all electric vehicle models studied have Lithium ion batteries, with a nominal capacity of around 20-40KWh. The models analysed were: Renault Zoe, BMW I3, NISSAN LEAF and Hyundai KONA. On the other hand, the estimation of available second-life electric vehicle battery energy storage capacity between the years 2025-2030 is 20,552kWh.

Taking into account that this figure would represent the available capacity in the most optimistic scenario according to the hypotheses that have been assumed in the study, these are too low figures to represent a possible large-scale storage system on the island of Tenerife. However, looking at the projections for the growth of electric vehicle fleet for 2030, all seems to indicate that the available second-life electric vehicle battery energy storage capacity will increase considerably towards the 2040s. Perhaps then second-life batteries can be used in large-scale energy storage applications on the island of Tenerife.

6. Case Study: Use of second-life electric vehicle batteries to store wind energy in Tenerife

In this section, the main results obtained in the project of technical and economic feasibility of the use of second-life battery energy storage system in a real wind farm to avoid power reduction has been presented.

The wind farm under study is called ICOR and is located in the south of the island of Tenerife, in the municipality of Arico. This wind farm has 6 Siemens Gamesa wind turbines. The wind turbine model used is SG 3.4-132, which offers 3.465MW of nominal power. This allows the wind farm to have an installed capacity of 20.79MW. It is the wind farm with the highest wind power so far on the island under analysis.

To carry out the proposed study, the electricity pool price in Tenerife had to be analysed, since knowledge of this variable is vital for calculating the economic gains or losses obtained in the project. From the analysis carried out on the electricity pool price in Tenerife between 2017 and 2020, we can conclude that the average electricity pool price is 54.47€/MWh, and values can be obtained within the range 4.94-140.79€/MWh (ignoring some values outside of range due to a blackout that occurred on the island in September 2019). It should be noted that the electricity pool price begins to be more unstable as of December 2018, due to the greater penetration of renewable generation, especially wind, in the island's energy mix.

It has been observed that the electricity pool price is usually higher in the months of January, October and November, reaching values around 60€/MWh on average. However, the electricity pool price will decrease in the months of March, April, May and June, with average values around 54€/MWh. These results are shown in Figure 14. On the other hand, Figure 15 shows the average daily behaviour of the electricity pool price. It can be seen how the hours in which the electricity pool price is higher, with values around 63€/MWh, correspond to the hours of greatest demand in Tenerife, that is, between 7:00 p.m. and 9:00 p.m., while the lowest prices, with values lower than 53€/MWh, are obtained in the hours of least demand, that is, between 1:00 a.m. and 6:00 a.m.

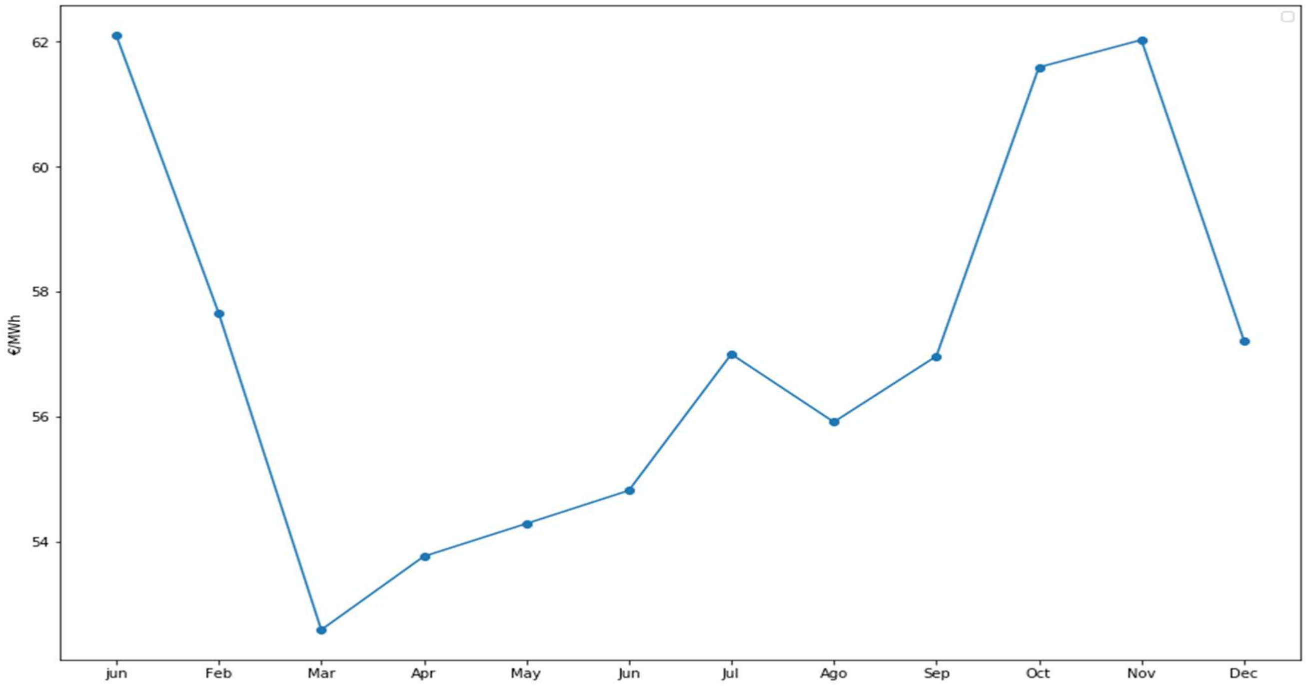

Figure 14. Seasonal behaviour of electricity pool price.

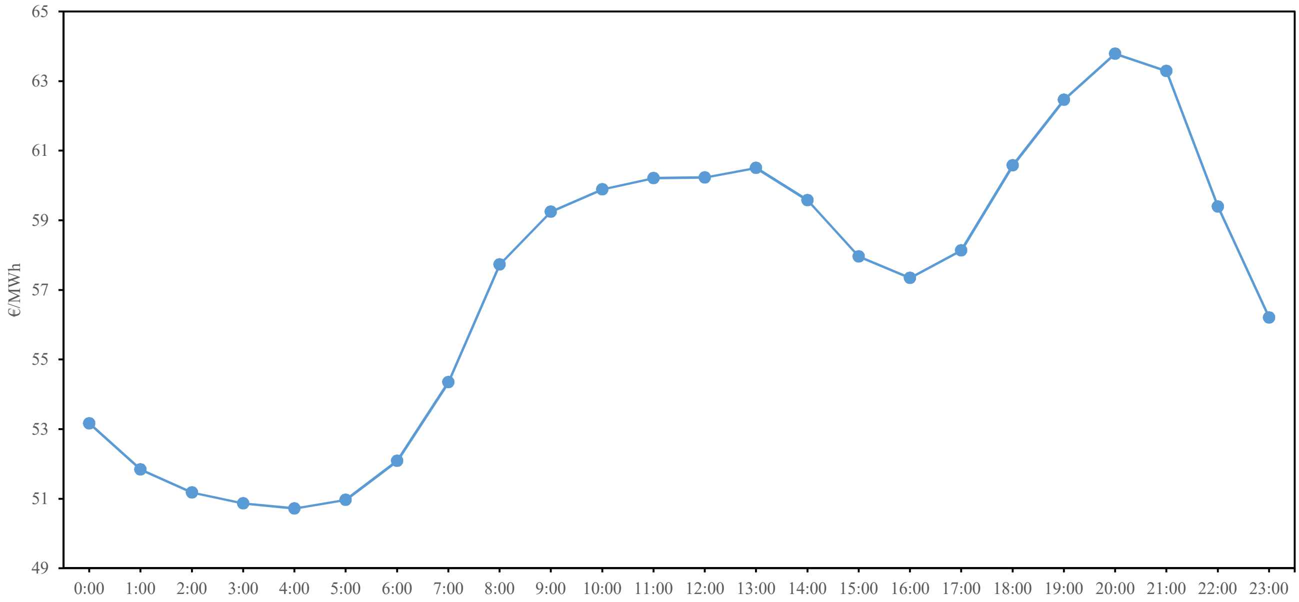

Figure 15. Daily profile of electricity pool Price.

The study of the wind resource at the ICOR wind farm site, that is, in Arico, is also essential to be able to consolidate a scenario on which to base our research. The results on the behaviour of the wind speed between December 31, 2017 and August 1, 2020 are characterized by an average speed of 3.8m/s and a range of average speeds between 0-11.64m/s. Regarding seasonal behaviour of the wind speed, we can observe that the wind resource is greater in the central months of the year, especially in the months of July and August, reaching average values around 5m/s. However, the wind resource is lower during the months of January, February, April and October, with average values below 3.5m/s (Figure 16).

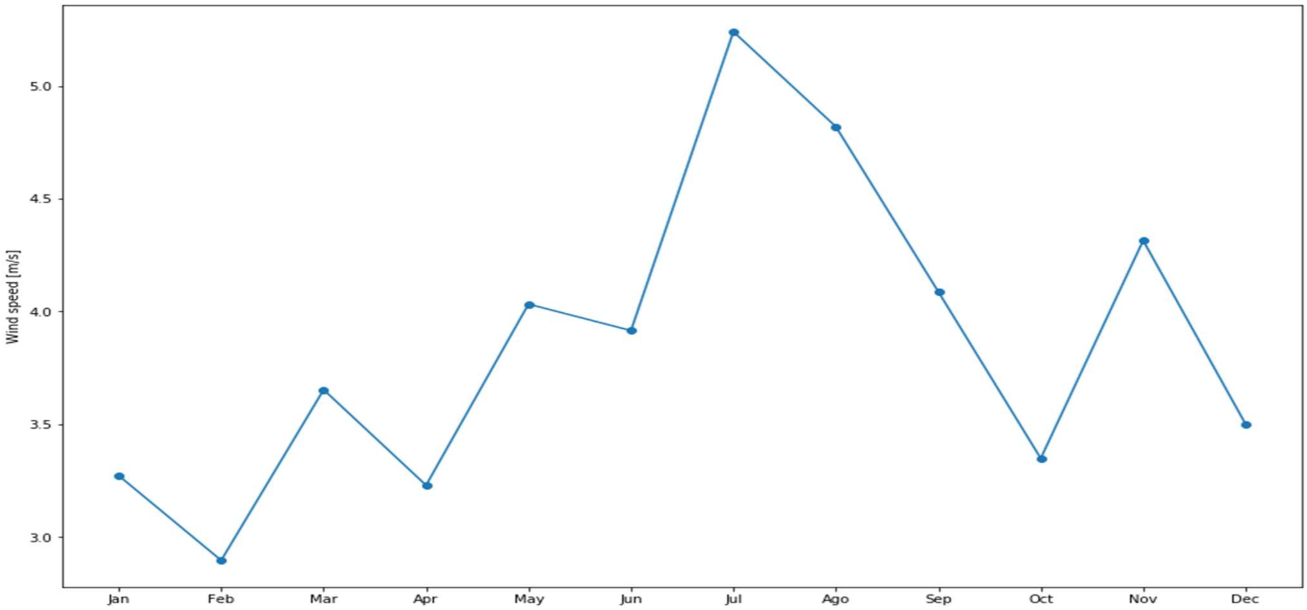

Figure 16. Seasonal behaviour of wind speed in Arico.

In addition, Figure 17 shows the daily profile of the wind speed obtained in Arico. In this case, we can see that wind speed is higher in the afternoon, that is, between 12 and 17 p.m., with average values between 4 and 4.4m/s, while it takes considerably lower values on average between 0 and 9 a.m. In order to be able to extract information on possible power reductions due to a high wind resource and low electricity demand, a comparison between the daily profile of wind speed in Arico and the daily profile of electricity demand in Tenerife has been made. It appears that power reductions occur during off-peak hours, that is, at those times when demand is reduced due to lower electricity consumption on the island.

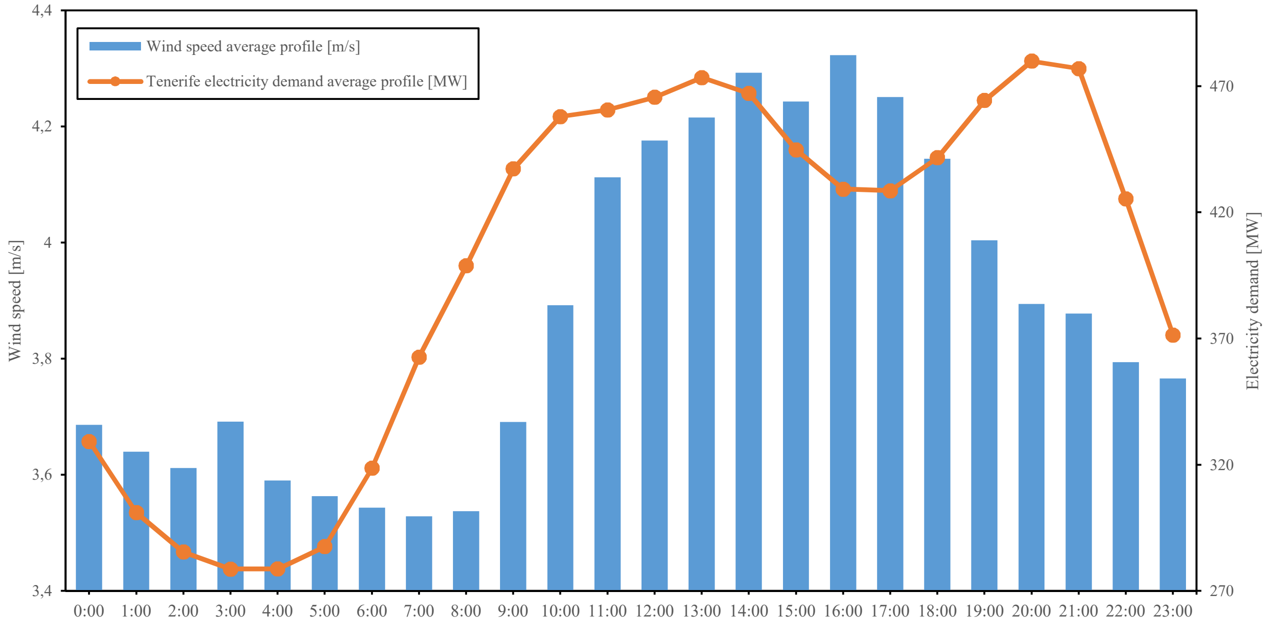

Figure 17. Daily profile of wind speed in Arico. Tenerife demand profile comparison.

Before drawing conclusions, it is important to take into account the results obtained in the analysis of the ICOR wind farm production, as well as the power reductions suffered by the wind farm during the study period (2018-2020). These results are summarized in Table 9. It should be noted that the average wind power injected into the grid by ICOR is 5.50MW, operating between a power range between 0-20.79MW. However, peaks of 21.11MW have been recorded. Regarding the power limitations established by REE to the wind farm, it can be said that the average is 19.66MW, which means a reduction of average power with respect to the nominal power of the wind farm of 1.29MW. However, in less than 25% of the analysed data set, power reductions have been found, which leads us to conclude that power limitations in ICOR are not frequent. However, this is not to say that they are not important in terms of energy waste.

Table 9. Analysis of ICOR Wind Farm power generation between 2018-2020.

	ICOR Wind Farm generation (MW)	Power Limitations (MW)	Nominal Power Reduction (MW)
mean	5.50	19.66	1.29
std	6.50	4.45	4.92
min	0	0	0
25%	0	20.79	0
50%	2.39	20.79	0
75%	9.83	20.79	0
max	21.11	20.79	20.79

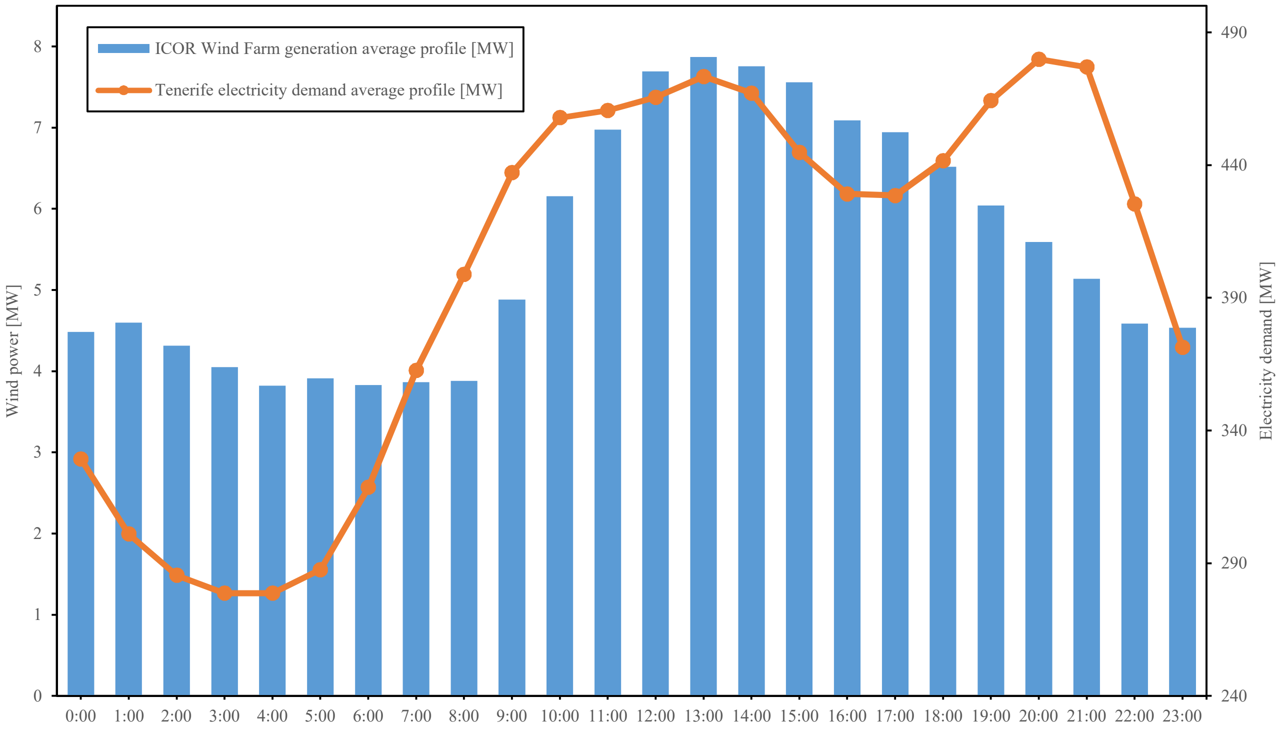

Figure 18. Daily profile of ICOR Wind Farm generation. Tenerife demand profile comparison.

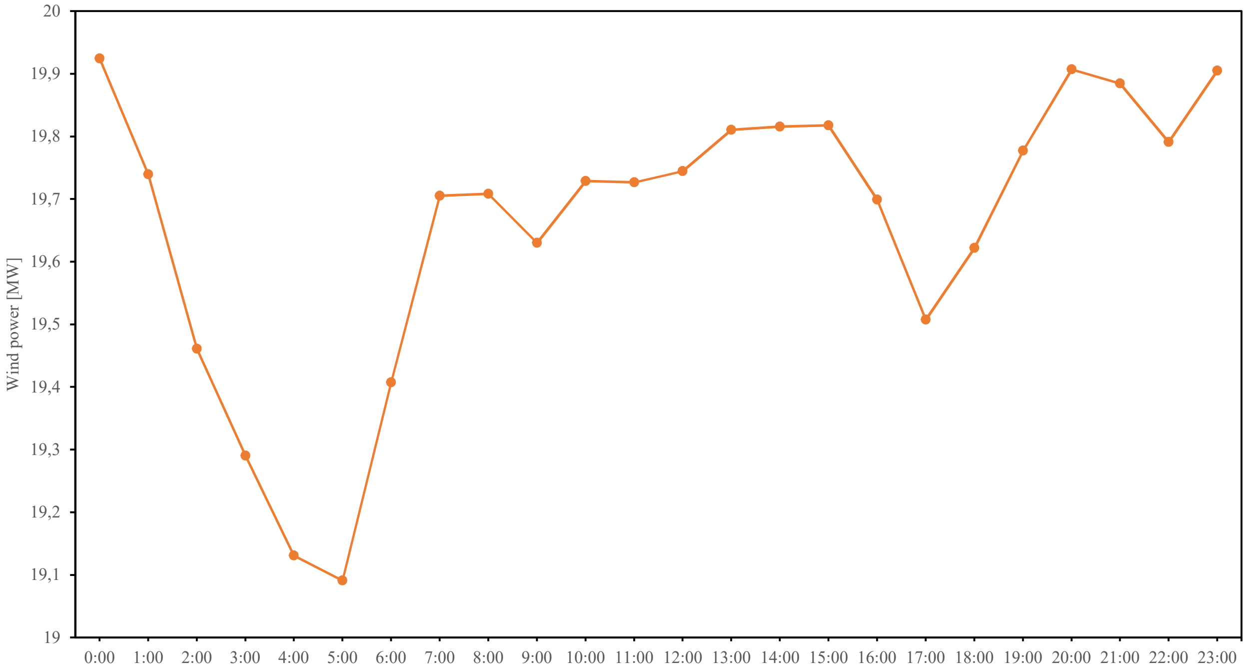

Figure 19. Daily profile of ICOR Wind Farm power reduction.

Figure 18 shows the daily production profile of ICOR Wind Farm, taking into account all the data analysed between 2018 and 2020. This profile has allowed us to characterize the average daily production of this wind farm. In general, ICOR reaches its highest production in the central hours of the day, that is, between 12 and 15 p.m., while its production is usually lower in the early morning hours, between 0 and 8 p.m. This behaviour is as expected, after having observed the wind speed profile in Arico.

Therefore, we could conclude that the power reductions in ICOR can be expected especially in the early morning hours, where electricity demand tends to decrease, thus increasing the difficulty of injecting wind energy into the Tenerife electricity grid at times of good wind resource during these hours. This is so due to the stochastic nature of wind energy and the priority of the electrical system operator to maintain energy security.

Figure 19 shows the profile of the power limitations by REE, according to the analysis of the hourly data of ICOR's operation between 2018-2020, provided by DISA RENOVABLES S.L. It has been confirmed that on average, the hours in which the ICOR Wind Farm is more prone to receiving power reductions are, by far, those located between 2 and 5 a.m. In addition, there can also be, although less frequently, power reductions at 5 p.m. This behaviour can also be corroborated by observing the comparison between the electricity demand profile in Tenerife and the ICOR generation profile (Figure 18).

The analysis carried out has allowed us to detect the possibility of storing "wasted" wind energy due to production limitations, in times of low electricity demand and good wind resources, and injecting it during the hours of greatest electricity demand, which coincide with those hours with a higher electricity pool in Tenerife, which would translate into higher revenues due to the use of energy storage. This would reduce energy waste due to power limitations in ICOR, as well as increase its load factor, by increasing the number of hours of operation.

Figure 20 shows the capacity and load factor of ICOR Wind Farm in 2019. The year 2019 has been analysed, since it is the only year for which we have all its data. In this analysis, it can be seen in which months the production is higher and in those months in which the wind farm has operated a greater number of hours. These months correspond to July, August and November. ICOR's capacity factor in 2019 was 28.69%, corresponding to some 2,513 equivalent hours in operation. As additional data, note that 2019 average daily wind energy was 143.14MWh, 2019 average monthly wind energy was 4,353.93MWh and 2019 total wind energy was 52,247.21.

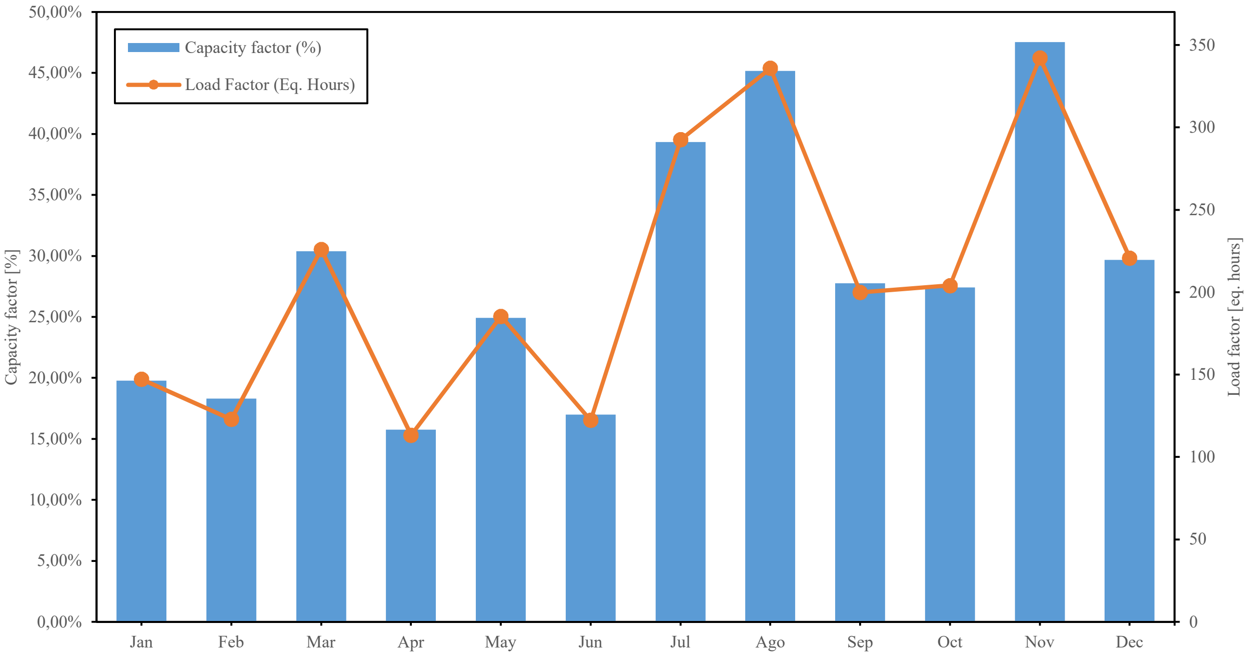

Figure 20. Capacity and load factor of ICOR Wind Farm in 2019.

Figure 21 shows the power curve obtained by adjusting the generation data of the ICOR wind turbines in the study period (2018-2020) and the wind resource of the site, by means of a polynomial regression of sixth grade. The fit obtained is quite good, achieving a coefficient of determination (R^2) of 0.96. This power curve has allowed us to modulate the power delivered by the wind farm under certain wind speed conditions, which has been very useful for simulating the scenarios to be studied.

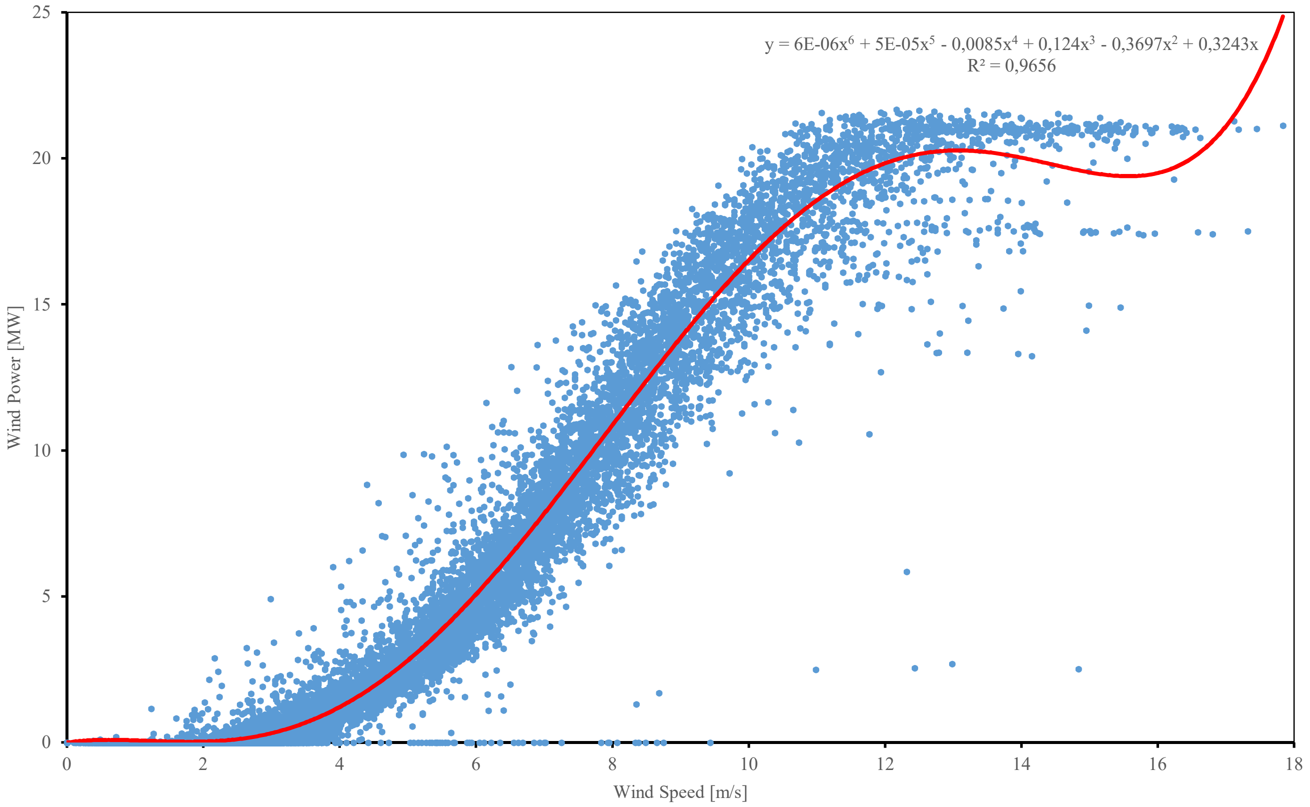

Figure 21. ICOR Wind Farm Power Curve (MW).

Two scenarios have been simulated below, taking into account what has been studied so far, that is, the behaviour of ICOR Wind Farm generation, power reductions in the wind farm, wind resource in Arico and the demand for electricity in Tenerife.

Table 10 summarizes the results obtained in Baseline Scenario. In this simulation, an annual generation of 49,229MWh has been obtained. The energy wasted in this typical year stands at 2,777MWh, which represents 5.64% of the total energy generated by the ICOR Wind Farm and it is reduced in economic losses of more than 125,000 euros per year. The average daily energy wasted is 0.32MWh. This situation has led us to estimate that the storage needed is 7.61MWh, so that we do not oversize the energy storage system.

Moreover, Table 11 shows the energy and economic balance obtained in the second scenario, that is, in a simulation in which a second-life battery energy storage system has been introduced to the ICOR Wind Farm. In this case, the total energy wasted annually represents 4.67% of the total energy generated by the ICOR Wind Farm with 2nd-life BESS. The power reductions in this wind farm are not significant. And in those moments in which they are, the available storage capacity cannot cope with the required storage need, since the power reductions are considerable, and can limit the ICOR Wind Farm production to 0MW, which would force to oversize the energy storage system.

Other interesting data from the study are that the total energy stored in second-life batteries was 478MW, of which 417MW have been injected into the grid, generating around 17,000 euros per year. On the other hand, information on the state of charge (SOC) of batteries has also been presented throughout the simulation. Specifically, it indicates what the average SCO of second life batteries, which gives us a vision of the average capacity that is being used by the system under study. It should also be said that the use of second-life batteries in the ICOR Wind Farm has allowed annual CO_2 emissions saving by energy injected into the grid from 2nd-life BESS of 267.64tonCO_2.

Table 10. Analysis of technical results in Baseline Scenario.

	ICOR Wind Farm Production Calculated [MWh]	"Wasted" Energy [MWh]	Economic Losses [€]
Jan	2,713.01	0.00	0.00
Feb	3,008.30	327.72	16,160.71
Mar	4,546.43	1,980.65	88,954.17
Apr	1,775.99	90.86	4,154.22
May	3,232.34	216.14	9,221.76
Jun	2,667.32	0.00	0.00
Jul	6,034.26	32.76	2,125.56
Ago	7,052.56	8.49	297.85
Sep	4,076.09	6.49	236.46
Oct	4,097.94	7.22	311.45
Nov	6,643.91	74.05	2,481.02
Dec	3,381.74	33.03	1,895.76
Total	49,229.89	2,777.41	125,838.95

Table 11. Analysis of technical results in ICOR Wind Farm with 2nd-Life BESS Scenario.

	ICOR Wind Farm Production Calculated [MWh]	2nd-Life BESS SOC [MWh]	"Wasted" Energy [MWh]	Economic Losses [€]	Stored Energy [MWh]	Energy injected from 2nd-Life BESS [MWh]	2nd-Life BESS Income [€]
Jan	2,713.01	0.76	0.00	0.00	0.00	0.66	35.53
Feb	3,008.30	1.94	204.73	10,546.70	122.99	106.82	4,576.90
Mar	4,546.43	3.79	1,802.93	81,783.72	177.72	154.67	5,972.33
Apr	1,775.99	1.06	42.60	2,068.03	48.26	41.96	1,741.22
May	3,232.34	1.80	139.47	5,892.90	76.67	66.67	2,671.40
Jun	2,667.32	0.76	0.00	0.00	0.00	0.00	0.00
Jul	6,034.26	0.88	25.91	1,685.15	6.85	5.96	317.33
Ago	7,052.56	1.08	1.27	44.68	7.21	6.27	258.06
Sep	4,076.09	0.79	0.97	35.47	5.52	4.80	188.98
Oct	4,097.94	1.07	1.08	46.72	6.13	5.31	233.28
Nov	6,643.91	2.85	60.22	2,056.98	13.84	12.05	389.54
Dec	3,381.74	1.20	19.33	1,178.37	13.70	11.91	580.05
Total	49,229.89	1.50	2,298.52	105,338.71	478.90	417.09	16,964.62

Finally, Table 12 shows the specifications and hypotheses assumed in the study of the economic viability of the proposal. The results obtained in the chosen economic viability indicators (NPV, IRR, Payback and DPP) have also been shown. The results indicate that a project with the characteristics studied here should not be accepted, at least in the year 2025. The price of reconditioning a battery for its use in a second stationary life is not yet low enough to make its use profitable in large-scale energy storage applications, despite being much cheaper than first-life lithium-ion batteries. This is so since the NPV obtained is negative (NPV = - 212,296.20 €), that is, the project it would not generate any net profit for shareholders, but losses. In addition, the project does not allow the recovery of the initial investment during the useful life of the second-life batteries used (Payback = + 10 years).

These results would be expected since the supply of second-life batteries does not yet represent a significant value for their price to drop and allow them to be economically viable in large-scale storage applications. Furthermore, in the specific case of the island of Tenerife, the estimated capacity of the batteries that will be withdrawn at the end of the next decade is still a very low value. Therefore, these results should not lead us to erroneous conclusions, since in the future, according to what has been studied in this research, wind power will increase as will the registrations of electric vehicles on the island. This situation will most likely lead to a greater supply of second-life batteries and a greater need for storage to avoid energy waste, since the amounts of wind energy, and renewable energy in general, injected into the grid will increase, and therefore, the power reductions by REE in order to ensure the electricity supply.

Table 12. Analysis of economical results in simulated scenario (ICOR Wind Farm with 2nd-Life BESS).

Specifications and hypothesis	
2nd-Life BESS useful capacity (MWh)	7.61
2nd-Life BESS useful life (years)	10
2025 2nd-Life BESS price (€/kWh)	55
2nd-Life BESS cost	418,514.52 €
ICOR Wind Farm Production –Calculated- (MWh)	49.229.89
Surplus Wind Energy (MWh)	2,777.41
Stored Energy (MWh)	478.90
Energy injected into the grid from 2nd-Life BESS (MWh)	417.09
2025 2nd-Life BESS estimated income	21,651.63 €
Depreciation	41,851.45 €
O&M costs (2nd-Life BESS)	100 €
Increase in 2nd-Life BESS estimated income	5%
CPI	1%
Tax rate	20%
Discount rate	7.09%
Results	
NPV	-212,296.20 €
IRR	-5.35%
Payback (years)	(+) 10
DPP (years)	(+) 10

However, due to the results of the economic viability analysis are not satisfactory according to the scenario we have established and the hypotheses we have assumed, a sensitivity analysis of the model has been carried out based on the price of second-life batteries. The objective of this analysis is to find the price from which the proposed project would begin to be economically viable. We must not forget that these results are valid exclusively for the case under study, that is, for the ICOR wind farm under the assumed hypotheses.

Table 13 shows the final results of the sensitivity analysis carried out. In this case, it is observed that for a price of reconditioning electric vehicle batteries for use in a second stationary life of around 22€/KWh, the proposed project begins to be economically viable. This price would allow an initial investment of 167,405.81€ for a 7.61MWh second-life battery energy storage system. It has been observed that, in this scenario, the proposed project could be accepted, since the NPV is positive and indicates that its implementation will probably allow the cost of the investment to be recovered, generate a net financial surplus (NPV = 3,685.15€), an IRR of 7.53% and a Payback period of approximately 7 years.

However, this is an approximation, since to be even more precise in the analysis, multiple variables that are very difficult to modulate should be taken into account, such as the effect of COVID-19 on the electric vehicle market and the renewable energy sector in the future. The situation we have been through makes it very difficult to make accurate predictions. Despite this, these are results that show that once the battery price barrier is overcome, its use in stationary applications will be a reality. In addition, it has the advantage that the price of this type of battery is much lower than that of new lithium-ion batteries, so this scenario is more likely to be reached in less time.

Table 13. Specifications, hypothesis and results of 2nd-Life BESS price sensitivity analysis.

Specifications and hypothesis (Sensitivity Analysis)	
2nd-Life BESS useful capacity (MWh)	7.61
2nd-Life BESS useful life (years)	10
2nd-Life BESS price (€/kWh)	***22***
2nd-Life BESS cost	167,405.81 €
ICOR Wind Farm Production –Calculated- (MWh)	49.229.89
Surplus Wind Energy (MWh)	2,777.41
Stored Energy (MWh)	478.90
Energy injected into the grid from 2nd-Life BESS (MWh)	417.09
2025 2nd-Life BESS estimated income	21,651.63 €
Depreciation	16,740.58 €
O&M costs (2nd-Life BESS)	100 €
Increase in 2nd-Life BESS estimated income	5%
CPI	1%
Tax rate	20%
Discount rate	7.09%
Results (Sensitivity Analysis)	
NPV	3,685.15 €
IRR	7.53%
Payback (years)	7.1
DPP (years)	7.2

7. Conclusions

Increasing energy demand and environmental challenges, such as global warming and climate change, requires a paradigm shift to take place in the ways of generating energy. Sustainable carbon-free energy sources must increase rapidly to replace the conventional generation systems. However, the increase in the use of renewable energy systems has produced an instability of the grid. These challenges require storage systems that provide viable power system operation solutions. For this reason, the use of second-life electric vehicle batteries has been proposed to design electrical energy storage systems at a lower cost. These battery energy storage systems allow to exploit surplus wind energy, at times of low electricity demand and high wind resources, to avoid power reductions.

In this work, the role of wind energy in the electricity generation structure and the electric mobility of the island of Tenerife has been studied, so that the capacity of second-life electric vehicle batteries that may be available in the future can be estimated. In addition, a technical and economic feasibility study has been carried out for the introduction of these battery energy storage systems in a real wind farm in Tenerife.

On the one hand, the electricity demand in Tenerife, between 2015 and 2020, ranges from 0-571.9MW, with an average of 396.5MW. A large part of the generation depends on conventional sources based on the use of fossil fuels. The generation technology that has the greatest participation in the power system is combined cycle and the technology with the lowest participation on average is the gas turbine. Fuel-Gas/Combined Cycle/Carbon plants represent 73.66% of total installed power in Tenerife, while photovoltaic and wind plants represent 8.14% and 15.05%, respectively. The generation on the island of Tenerife is quite centralized, since approximately 75% of the generation is concentrated in the south of it. Specifically, the installed wind power (195.92MW) is distributed among three municipalities: Arico, Granadilla de Abona and Buenavista del Norte.

A slight increase in electricity demand can be observed, going from an annual energy consumption of 3,407,291MWh in 2015 to an annual demand of 3,534,502MWh in 2019. Regarding the annual energy generation, it can be observed how combined cycles and steam turbines dominate production. Furthermore, annual wind energy has undergone significant changes, going from 71,915MWh in 2015 to 491,156MWh in 2019. The increase in annual wind energy generation on the island of Tenerife, going from 3% of 2015 total generation to 14% of 2019 total generation. Annual average of monthly wind power generation in Tenerife has suffered a significant increase in the last five years, especially in 2018 and 2019. It has gone from a monthly average of 5,993MWh in 2015 to 40,930MWh in 2019.

On the other hand, the vehicle fleet has increased from 768,924 vehicles in 2010 to 881,226 in 2020. Almost all the vehicles in Tenerife use gasoline or diesel as fuel. In 2020, gasoline vehicles represent 70.2% of the fleet and diesel vehicles 28.9%. Electric vehicles only represent 0.13% of 2020 vehicle fleet. However, the fleet of electric vehicles is the one that has grown the most. Electric vehicles have gone from being 83 in 2010 to 305 in 2015 and 1,159 in 2020.

2019 total vehicle registrations in the province of Santa Cruz de Tenerife was 36,139 and total electric vehicle registrations in the province of Santa Cruz de Tenerife represented 0.73%. The number of registrations in the province of Santa Cruz de Tenerife during 2020, so far, is 6,454 and the registrations of electric vehicles represents 1.67% of total registrations until May 2020. The forecast of annual registrations of electric vehicles in the province of Santa Cruz de Tenerife in the next decade indicates that the annual registrations of electric vehicles will grow exponentially in Tenerife, anticipating the annual registration of more than 2,000 electric vehicles by 2030, that is, approximately 10 times higher than the number of registrations produced in 2019. These are very encouraging results and they indicate that the deployment of electric vehicles in the province of Santa Cruz de Tenerife will begin to take place in the next decade. This would be very positive from the point of view of the work carried out, since the number of electric vehicle batteries that will be retired in the 2040s would increase significantly, offering greater viability to the idea proposed in this work.

However, the estimate of the energy storage capacity of second-life electric vehicle battery available between the years 2025-2030 is 20.55MWh, in the most optimistic scenario. These are too low figures to represent a possible large-scale storage system on the island of Tenerife nowadays. However, looking at the projections for the growth of electric vehicle fleet for 2030, all seems to indicate that the available second-life electric vehicle battery energy storage capacity will increase considerably towards the 2040s. Perhaps then second-life batteries can be used in large-scale energy storage applications on the island of Tenerife.

On the other hand, as analysed in the case study, the wind speed profile in Arico, the daily profile of electricity demand in Tenerife and the ICOR wind energy production indicate that power reductions occur during off-peak hours, that is, at those times when demand is reduced due to lower electricity consumption on the island. The analysis carried out has allowed us to detect the possibility of storing "wasted" wind energy due to production limitations in wind farms located in the south of Tenerife, in times of low electricity demand and good wind resources, and injecting it during the hours of greatest electricity demand, which coincide with those hours with a higher electricity pool in Tenerife, which would translate into higher revenues due to the use of energy storage. This would reduce energy waste due to power limitations in ICOR Wind Farms or other wind farms located in Arico (which are most of the wind farms in Tenerife), as well as increase its load factor, by increasing the number of hours of operation.

The scenarios based on real data that have been simulated in this work indicate that the annual energy waste due to power limitations in a wind farm such as ICOR can be around 6% of its total generation, which could suppose economic losses of more than 125,000€, as studied in this wind farm with 20.79MW of nominal power. A second-life battery energy storage system of 7.61MWh has been introduced in the simulation, obtaining a decrease in wasted energy of 1% compared to a scenario without batteries and a saving in CO_2 emissions of 267.64 tons of CO_2.

However, in the economic aspect the results were not satisfactory. These results would be expected since the supply of second-life batteries does not yet represent a significant value for their price to drop and allow them to be economically viable in large-scale storage applications. Therefore, these results should not lead us to erroneous conclusions, since in the future, according to what has been studied in this research, wind power will increase as will the registrations of electric vehicles on the island. This situation will most likely lead to a greater supply of second-life batteries and a greater need for storage to avoid energy waste, since the amounts of wind energy, and renewable energy in general, injected into the grid will increase, and therefore, the power reductions by REE in order to ensure the electricity supply.

Finally, it is observed that for a price of reconditioning electric vehicle batteries for use in a second stationary life of around 22€/KWh, the proposed project begins to be economically viable. However, this is an approximation, since the situation we have been through makes it very difficult to make accurate predictions. Despite this, these are results that show that once the battery price barrier is overcome, its use in stationary applications will be a reality. In addition, it has the advantage that the price of this type of battery is much lower than that of new lithium-ion batteries, so this scenario is more likely to be reached in less time. We must not forget that the use of second-life batteries as an energy storage system not only can result in an increase in the integration of renewable energy in the electricity grid and in a reduction in the cost of the electrical storage system, but also in a reduction of the environmental footprint by prolonging the useful life of the batteries for electric vehicles, offering added value to the whole system. In addition, it should be mentioned that theses energy storage systems can be quite interesting in several applications such as energy storage systems powered by photovoltaic energy for use in public lighting, for self-consumption applications or for frequency regulation. It is hoped to carry out some future studies that can justify what has been said. And, as a proposal for improvement, it is proposed to study whether the greater conversion losses of a less efficient second-life battery compensate for the emissions incorporated when manufacturing a new one.

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References

[1] IRENA, *Future of Wind*. 2019.

[2] M. Raoofat, M. Saad, S. Lefebvre, D. Asber, H. Mehrjedri, and L. Lenoir, "Wind power smoothing using demand response of electric vehicles," *Int. J. Electr. Power Energy Syst.*, vol. 99, no. November 2017, pp. 164–174, 2018.

[3] U. Akram, M. Nadarajah, R. Shah, and F. Milano, "A review on rapid responsive energy storage technologies for frequency regulation in modern power systems," *Renew. Sustain. Energy Rev.*, vol. 120, no. October 2019, p. 109626, 2020.

[4] Z. Jiang, X. Han, Z. Li, W. Li, M. Wang, and M. Wang, "Two-stage multi-objective collaborative scheduling for wind farm and battery switch station," *Energies*, vol. 9, no. 11, pp. 1–17, 2016.

[5] N. Nguyen and J. Mitra, "An analysis of the effects and dependency of wind power penetration on system frequency regulation," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 354–363, 2016.

[6] Z. Zhang, D. Mei, H. Jiang, G. Liu, H. He, and Y. Chen, "Mode for reducing wind curtailment based on battery transportation," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 6, pp. 1158–1171, 2018.

[7] P. Hou, G. Yang, P. Enevoldsen, and A. H. Nielsen, "Cooperation of Offshore Wind Farm with Battery Storage in Multiple Electricity Markets," *Proc. - 2018 53rd Int. Univ. Power Eng. Conf. UPEC 2018*, pp. 1–6, 2018.

[8] M. Elkazaz, M. Sumner, and D. Thomas, "Energy management system for hybrid PV-wind-battery microgrid using convex programming, model predictive and rolling horizon predictive control with experimental validation," *Int. J. Electr. Power Energy Syst.*, vol. 115, no. July 2019, p. 105483, 2020.

[9] E. González-Rivera, R. Sarrias-Mena, P. García-Triviño, and L. M. Fernández-Ramírez, "Predictive energy management for a wind turbine with hybrid energy storage system," *Int. J. Energy Res.*, vol. 44, no. 3, pp. 2316–2331, 2020.

[10] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015.

[11] S. Zhan *et al.*, "Co-optimized trading of hybrid wind power plant with retired EV batteries in energy and reserve markets under uncertainties," *Int. J. Electr. Power Energy Syst.*, vol. 117, no. October 2019, p. 105631, 2020.

[12] Z. Huang *et al.*, "Modeling and multi-objective optimization of a stand-alone PV-hydrogen-retired EV battery hybrid energy system," *Energy Convers. Manag.*, vol. 181, no. August 2018, pp. 80–92, 2019.

[13] E. Martinez-Laserna *et al.*, "Technical Viability of Battery Second Life: A Study from the Ageing Perspective," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2703–2713, 2018.

[14] E. Martinez-Laserna *et al.*, "Evaluation of lithium-ion battery second life performance and degradation," *ECCE 2016 - IEEE Energy Convers. Congr. Expo. Proc.*, 2016.

[15] Y. Tang, Q. Zhang, H. Li, Y. Li, and B. Liu, "Economic analysis on repurposed EV batteries in a distributed PV system under sharing business models," *Energy Procedia*, vol. 158, pp. 4304–4310, 2019.

[16] S. I. Sun, A. J. Chipperfield, M. Kiaee, and R. G. A. Wills, "Effects of market dynamics on the time-evolving price of second-life electric vehicle batteries," *J. Energy Storage*, vol. 19, no. May, pp. 41–51,

2018.

[17] M. Zhu, Z. Liu, J. Li, and S. X. Zhu, “Electric vehicle battery capacity allocation and recycling with downstream competition,” *Eur. J. Oper. Res.*, vol. 283, no. 1, pp. 365–379, 2020.

[18] Vatsala, R. H. Khan, Y. Varshney, A. Ahmad, M. S. Alam, and R. C. Chaban, *ISGW 2017: Compendium of Technical Papers*, vol. 487. 2018.

[19] K. Richa, C. W. Babbitt, N. G. Nenadic, and G. Gaustad, “Environmental trade-offs across cascading lithium-ion battery life cycles,” *Int. J. Life Cycle Assess.*, vol. 22, no. 1, pp. 66–81, 2017.

[20] N. Tam Thanh, N. Maik, T. Cong Nam, and J. Andreas, “Techno-Economic Evaluation of Energy Storage Systems Built from EV Batteries - Prospective Revenues in Different Stationary Applications,” *E3S Web Conf.*, vol. 64, 2018.

[21] R. Xiong, Y. Zhang, J. Wang, H. He, S. Peng, and M. Pecht, “Lithium-Ion Battery Health Prognosis Based on a Real Battery Management System Used in Electric Vehicles,” *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 4110–4121, 2019.

[22] “NISSAN | THE REBORN LIGHT | Reborn to keep serving humans.” [Online]. Available: http://www.nissan.co.jp/THEREBORNLIGHT/EN/. [Accessed: 26-May-2020].

[23] A. A. Chen, A. J. Stephens, R. Koon Koon, M. Ashtine, and K. Mohammed-Koon Koon, “Pathways to climate change mitigation and stable energy by 100% renewable for a small island: Jamaica as an example,” *Renew. Sustain. Energy Rev.*, vol. 121, no. January, p. 109671, 2020.

[24] IRENA, “SMALL-ISLAND POWER SYSTEMS,” 2018.

[25] IRENA, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*. 2019.

[26] G. N. Psarros and S. A. Papathanassiou, “Evaluation of battery-renewable hybrid stations in small-isolated systems,” *IET Renew. Power Gener.*, vol. 14, no. 1, pp. 39–51, 2020.

[27] A. R. Dehghani-Sanij, E. Tharumalingam, M. B. Dusseault, and R. Fraser, “Study of energy storage systems and environmental challenges of batteries,” *Renew. Sustain. Energy Rev.*, vol. 104, no. November 2018, pp. 192–208, 2019.

[28] IRENA, *Electricity Storage Valuation Framework*, no. March. 2020.

[29] T. M. Gür, “Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage,” *Energy Environ. Sci.*, vol. 11, no. 10, pp. 2696–2767, 2018.

[30] F. Nadeem, S. M. S. Hussain, P. K. Tiwari, A. K. Goswami, and T. S. Ustun, “Comparative review of energy storage systems, their roles, and impacts on future power systems,” *IEEE Access*, vol. 7, pp. 4555–4585, 2019.

[31] A. Saez-De-Ibarra, E. Martinez-Laserna, D. I. Stroe, M. Swierczynski, and P. Rodriguez, “Sizing Study of Second Life Li-ion Batteries for Enhancing Renewable Energy Grid Integration,” *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 4999–5007, 2016.

[32] IRENA, “Solutions to integrate high shares of renewable energy,” no. June, p. 28, 2019.

[33] “Alphabet Wants to Fix Renewable Energy’s Storage Problem — With Salt - Bloomberg.” [Online]. Available: https://www.bloomberg.com/news/articles/2017-07-31/alphabet-wants-to-fix-renewable-energy-s-storage-problem-with-salt. [Accessed: 12-Aug-2020].

[34] I. Renewable and E. Agency, *ELECTRICITY STORAGE AND RENEWABLES : COSTS AND MARKETS TO 2030*, no. October. 2017.

[35] P. Gardner *et al.*, “WORLD ENERGY COUNCIL World Energy Resources,” 2016.

[36] M. Aneke and M. Wang, “Energy storage technologies and real life applications – A state of the art review,” *Appl. Energy*, vol. 179, pp. 350–377, 2016.

[37] T. Kim, W. Song, D. Y. Son, L. K. Ono, and Y. Qi, “Lithium-ion batteries: outlook on present, future, and hybridized technologies,” *J. Mater. Chem. A*, vol. 7, no. 7, pp. 2942–2964, 2019.

[38] H. S. Saini, T. Srinivas, and D. M. V. Kumar, *Innovations in Electrical and Electronics Engineering*. 2019.

[39] IRENA, *Innovation Outlook - Smart charging for electric vehicles*. 2019.

[40] “Bienvenido | ESIOS electricidad · datos · transparencia.” [Online]. Available: https://www.esios.ree.es/es. [Accessed: 25-Aug-2020].

[41] “Portal estadístico.” [Online]. Available: https://sedeapl.dgt.gob.es/WEB_IEST_CONSULTA/. [Accessed: 26-Aug-2020].

[42] H. Rallo, L. Canals Casals, D. De La Torre, R. Reinhardt, C. Marchante, and B. Amante, “Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases,” *J. Clean. Prod.*, vol. 272, p. 122584, 2020.

[43] “Dark Sky - Broadway, New York, NY.” [Online]. Available: https://darksky.net/forecast/40.7127,-74.0059/us12/en. [Accessed: 02-Sep-2020].

[44] “Inicio | IDAE.” [Online]. Available: https://www.idae.es/. [Accessed: 01-Sep-2020].

[45] “La CNMC publica la metodología de cálculo de la tasa de retribución financiera de las actividades del sector eléctrico para el periodo 2020-2025 | CNMC.” [Online]. Available: https://www.cnmc.es/2018-11-02-la-cnmc-publica-la-metodologia-de-calculo-de-la-tasa-de-retribucion-financiera-de-las. [Accessed: 02-Sep-2020].