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Wind farm energy surplus storage solution with second-life vehicle batteries in isolated grids

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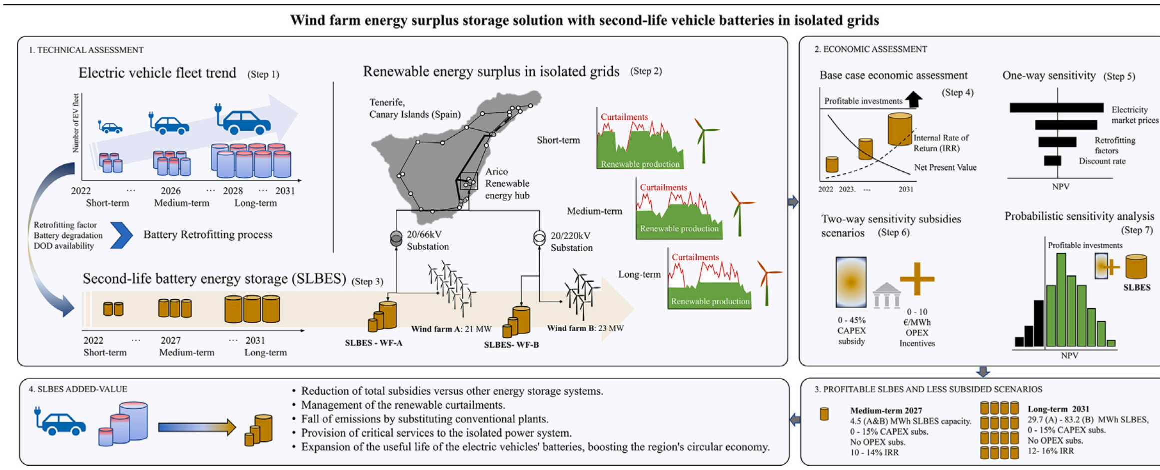
GRAPHICAL ABSTRACT



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ABSTRACT

Energy storage, demand-side response, and electromobility expansion are important issues in the energy transition towards the goal of carbon neutrality. Automobile fleet electrification entails not only a reduction in emissions, but also an improvement in energy efficiency. However, the accumulation of batteries in landfills represents a huge problem in the medium-long term. These challenges become more relevant for islands. This article proposes to reuse batteries that are no longer useful for transportation as energy storage to recover renewable energy surpluses. A methodology for the techno-economical assessment of second-life car batteries as a storage solution in wind farms is presented. This method was successfully applied in two wind farms located on Tenerife island. The results delve into the feasibility of the solution, environmental impact, and government policies in terms of subsidy support. Moreover, extending the battery lifespan contributes to the circular economy, which aligns with the United Nations sustainable development goals on affordable and clean energy. In conclusion, second-life batteries could play an essential role as energy storage in the medium-long term on isolated systems.

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1. Introduction

In the years to come, a profound energy transformation towards low-carbon technologies will be essential. This deployment will greatly depend on the availability of efficient solutions for renewable energy grid integration. However, existing electrical grid systems are not designed to handle a large-scale integration of renewable power sources without serious grid outages. This is causing a limitation in the penetration of renewable energies, above all, in isolated electrical systems in which there are additional technical challenges such as power flexibility requirements and fast-response backup reserves (International Renewable Energy Agency, 2019).

Both the intermittent nature of renewable energy resources, and their energy fluctuations over multiple time horizons increase the complexity of electricity grid planning and operation (Akram et al., 2020). Such problems pose the main barriers, from a technical point of view, to the massive implementation of solar photovoltaic and wind technologies in fragile isolated electrical systems (Nadeem et al., 2019; Ramos-Real et al., 2018). Renewable energy plants must meet certain rules and requirements to be able to connect to the grid, in compliance with the ramp rates from the conventional backup reserves (Saez-De-Ibarra et al., 2016). Managing the integration of high amounts of variable renewable energy requires flexibility from all sectors of the energy system, i.e., power generation, transmission and distribution systems, energy storage systems (ESSs), and, increasingly, demand side (IRENA, 2019a; Díaz et al., 2015; Ramirez-Diaz et al., 2016).

ESSs provide robustness and flexibility throughout the energy sector, enabling high penetration of renewable energies into the system. In addition, ESSs provide valuable applications, such as demand response, provision of auxiliary services, quick reserve capacity, reliable power supply for isolated grids, peak-power shaving, and compensation of transmission and distribution grids (Nguyen and Mitra, 2016). Nevertheless, most ESSs have yet to face key requirements beyond the technical ones, such as the supply chain of materials, their high costs, their robustness, their life cycles, their roundtrip efficiency and their environmental impact (Zhang et al., 2018).

Lithium-ion is the most popular battery technology today. This technology is used in most electric vehicles (EVs) and portable devices due to its trade-off between energy density and weight. For large scale storage, lithium-ion based batteries are used both on photovoltaics and wind farms to improve their penetration on grids (Simpson et al., 2021; Li et al., 2021; D'amico et al., 2021; Dui et al., 2018; Ghasemi et al., 2016; Sundararagavan and Baker, 2012). Current concerns about this technology are related to cost, availability of materials, and the supply chain environmental and social impacts. Although costs of battery energy storage systems are falling sharply, it is necessary to carry out a thorough analysis to guarantee its profitability before investment (LAZARD, 2019). Besides, there is a growing interest in how to expand the life of batteries as much as possible, through second-life applications, and how to recycle after end-of-life to reduce the environmental impact of the technology.

Second-Life Battery Energy Storage (SLBES) may improve not only the share of renewable but also the reuse of batteries from regional old electric cars in a second-life, hence extending their useful lifespan and reducing their environmental footprint. Certainly, the recovery, treatment, and assembly of SLBES entail large investment costs, in addition to the purchase of electricity surplus from renewable sources, and maintenance, which also involves an operational cost. Nevertheless, governments should be interested in promoting these solutions to reduce the impact on the environment.

Second-life batteries cannot outperform first-life batteries in terms of state of health (SOH) and lifespan. However, this technology provides an added value from the environmental point of view, since it extends the life of batteries before being recycled. For this reason, the use of second-life batteries fits within the objectives of the main circular economy action plans of the European Union (EU), The European Green Deal and The 2030 Agenda and the Sustainable Development Goals (European Commission, 2020a, 2019; United Nations, 2016). Furthermore, a new proposal for EU framework battery regulation is under development (Bonafè, 2020). These plans promote a new production and consumption model that maintains the value of products, materials and resources as long as possible, and reduces the generation of waste.

This article proposes a techno-economical analysis of the use of second-life batteries as energy storage in wind farms. The main contributions of the article are related to the conclusions obtained on the feasibility of this technology. The variables affecting the techno-economical performance of the solution, and the conditions that grant its feasibility are explored. Both the methodology and its application on real scenarios in an isolated system are presented. Furthermore, the study proposes an empirical approach on how to manage, both technically and economically, new investments in energy storage. The paper also focuses on the role of governments by highlighting the critical points that must be reinforced or supported to achieve the objectives of EU on sustainable energy transition, and the goals of United Nations on sustainable development in other similar isolated regions.

The rest of the paper is organized as follows: Section 2 shows a review of potential uses of SLBES as energy storage. Section 3 presents and motivates the case study located on the Tenerife isolated electrical system. Later, Section 4 details the methodology of the techno-economic analysis, including the modeling of potential SLBES from EV fleet, the analysis of renewable energy surplus and the basis of the economic assessment. Section 5 explains the results. Finally, Section 6 discusses the policy implications of our approach, and summarizes our main conclusions.

2. Second-life electric vehicle batteries as energy storage system

As stated above, the future of power systems and renewable energy integration is closely related to the availability of effective methods to store that energy. Costs and environmental impact aside, battery energy storage systems are the most effective electrochemical technology for stabilizing power grids (IRENA, 2017). The focus of this study will be on lithium-ion batteries as they are lighter, smaller and more powerful than other batteries, and, specifically, they are massively used in EVs.

In general, Li-based battery systems are characterized by high energy and power density, stable cycle, low self-discharge rate, wide design flexibility, near-zero memory effect, fast response time (milliseconds), high efficiency, and low maintenance. In addition, their costs have significantly decreased over the years, while energy density and power have increased. However, lithium-ion batteries are fragile, require a special protection circuit to avoid overcharging, frequent charging, and have a high capital cost, which limits their use for massive capacity applications. Furthermore, the useful life of lithium-ion batteries is sensitive to over-discharge, high temperatures (above 45 °C) and aging (Nadeem et al., 2019; Dehghani-Sanij et al., 2019; Gür, 2018; Aneke and Wang, 2016; Kim et al., 2019; Saini et al., 2020).

The chemistry of the Lithium-ion batteries determines key technical characteristics, as well as aspects of safety, cost, and lifespan (Miao et al., 2019; Houache et al., 2022). For lithium nickel cobalt aluminum oxide (NCA) and lithium nickel manganese cobalt oxide (NMC), the specific energy fluctuates between 150–260 Wh/kg. In terms of lifespan, these batteries reach around 400–1500 cycles at 80% of capacity. This degradation depends directly on the discharge conditions, the operational depth of discharge (DOD), discharge rate and environment temperature (Preger et al., 2020).

Nowadays, the expansion of the EVs is a reality and, in the coming years it is expected that they will dominate the automotive market. NMC and NCA batteries, with 71% and 23% of market share respectively, are the most predominant technologies. According to the International Energy Agency (IEA) trends, the worldwide EVs market share in 2030 will achieve 16%, which represents a total sales of 27 million vehicles per year on the stated government scenarios (International Energy Agency, 2022). This situation poses a great challenge for battery suppliers and recycling facilities because the demand for lithium will multiply by 15 and that for cobalt by 10 in 2030 (IRENA, 2019b; Martinez-Laserna et al., 2016; Bonafè, 2020).

It is also important to mention that Li-based batteries generate environmental pollutants, including hazardous waste, greenhouse gas (GHG) emissions, and toxic fumes during manufacturing and recycling. According to EU figures, in 2019, a total of 51% of batteries sold were collected for further recycling. The new EU policy proposal on batteries raises these figures to 70% for portable batteries, 85% for light means of transport batteries and 100% for automotive, industrial and electric vehicle batteries by 2025 (Bonafè, 2020).

Fortunately, an alternative to recycling recalled EVs batteries is to recondition and reuse them in stationary applications. In accordance with (Richa et al., 2017), the SLBES offsets initial manufacturing impacts by extending the battery lifespan, as well as preventing the production of new batteries with the same purpose. Batteries removed from EVs still have enough capacity to be reused, could be obtained cheaply, and may satisfy between 61%–124% of the demand of utility-scale lithium-ion battery storage in 2030 (Engel et al., 2019). The reuse of batteries removed from EVs in renewable energy systems is a relatively new concept. SLBES are defined as those that are removed from EVs when their energy density has degraded below the level required for transport, but are useful enough for less demanding applications, like stationary energy storage (Zhan et al., 2020; Huang et al., 2019; Martinez-Laserna et al., 2018).

In short, this second-life offers an extension of up to 10 years in battery life, at a compelling price, which in 2021 is estimated at around 85 €/kWh (Sun et al., 2018). Apart from the additional monetizing of the battery after it served the primary purpose, this second life will also offer savings in the manufacturing of new battery cells, and a delay in the recycling of the batteries, postponing related regulatory responsibilities. Conversely, the benefits of second-life use can only be achieved once certain drawbacks are addressed; the battery reconditioning cost, and its shorter service life and lower efficiency are the main ones. Besides, warranty issues and social and regulatory barriers to the adoption of SLBES have to be considered. In this sense, the commitment and collaboration of the automotive original equipment manufacturers would be crucial for a well-founded cells selection, and for SLBES to be a technically viable concept (Martinez-Laserna et al., 2016, 2018; Tang et al., 2019).

Despite the fact that SLBES technology has not yet reached an acceptable level of maturity that guarantees its profitability and reliability, it is beginning to attract the attention of major original equipment manufacturers such as Nissan-Renault, BMW, Tesla or Daimler (Vatsala et al., 2018; Tam Thanh et al., 2018). For example, Nissan is promoting a ground-breaking project to reuse its EV batteries for public lighting in Fukushima (Xiong et al., 2019). Other project located in UK combines domestic photovoltaic and energy storage system to 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 with SLBES in partnership with Eaton (González-Rivera et al., 2020). Apart from these examples, there are numerous experiences (mainly living-lab experiences or new business models) that use second-life batteries for various applications, such as auxiliary services, network deferral, energy management, or domestic use (Hossain et al., 2019).

3. Case study: A wind energy hub in Tenerife

Today's climate and environmental challenges require an urgent and ambitious response. Recently, the EU has endorsed more ambitious targets for a reduction in GHG emissions, by 2030, of at least 55% compared to 1990 values and carbon neutrality by 2050. The required reduction of emissions from the transport sector is estimated to be 90% by 2050 in accordance with the Sustainable and Smart Mobility Strategy of the EU (European Commission, 2020b).

At the national level, we must mention the National Integrated Energy and Climate Plan (PNIEC) 2021–2030, which defines the objectives of reducing GHG emissions, penetration of renewable energies and energy efficiency (MITECO, 2020). The PNIEC objectives for 2030 are: 23% reduction in GHG emissions compared to 1990; 42% of renewables on the final use of energy; 39.5% improvement in energy efficiency; and 74% renewable energy in electricity generation. By 2050, the aim is to achieve a 100% renewable electricity system and full decarbonization. In addition, the new Law on Climate Change and Energy Transition, recently approved, will help Spain meet its international commitments in the fight against climate change (BOE, 2021a).

Specifically, the plans of the Canary Islands for energy transition (PTECan) aim at the total decarbonization of the archipelago by 2040. To achieve such objectives, it is necessary to install renewables at a rate of about 500 MW per year before 2040, and to deploy a specific strategy for ESS and energy management (ENDESA and Monitor Deloitte, 2020; Instituto Tecnológico de Canarias, 2022). The implementation of ESSs in Tenerife could mitigate the effects of renewable energy curtailments, storing the excess from renewable sources and subsequently injecting this energy into the grid at peak hours or providing complementary services to the electric power system (regulation of frequency, voltages, rolling reserves, secondary, or tertiary) (NREL and U.S. Department of Energy, 2020). However, there is no medium-term strategy to install massive ESSs (more than 1 GWh) on the island.

The case study is located in Tenerife, the most populated (around one million inhabitants) and the largest island in the Canary Archipelago. Tenerife's electric power system is currently isolated from the rest of Canary islands. This electrical system is the largest in terms of electricity demand and installed power (both renewable and conventional). Renewable power installed is made up of a 195.7 MW of wind power and about 107.2 MW of photovoltaic on the island (Gobierno de Canarias, 2020). In relation to the size of the system by 2019, the average peak demand was around 490 MW (at 20:00), while the overnight demand of the system was nearly 287 MW (at 4:00). Undoubtedly, the island's economic activity based on tourism and a limited participation of the industrial sector cause a low overnight electricity demand, increasing the difficulty of manageability of it by the transmission system operator (TSO). Remarkably, Tenerife is not subject to seasonal demand peaks during summers or winters due to its almost constant flow of tourists and the mild temperatures year round.

Fig. 1 shows the limitations due to excess renewable sources set by the TSO, which usually occur on weekends (due to the decrease in demand) and mainly during night hours. Under these renewable curtailment conditions, conventional technologies not only tend to reduce their load at the minimum operating level, but also maintain the required reserves (Ministerio de Industria Energía y Turismo, 2015). Thus, conventional plants ensure the operation of the system with one combined cycle working at 75–110 MW load, one steam turbine at 46–60 MW load and one or two reciprocating diesel engines at minimum load, adding 10–15 MW of power. Therefore, the margin for the introduction of wind power is usually limited to 100–156 MW, and the remaining power available during these highly-wind hours is curtailed.

Our case study evaluates two wind farms that are located in one of the largest renewable energy hubs on the island (Fig. 2). Nowadays, these wind farms represent around 23% of the installed wind power in the island. The case study comprises two substations, one for wind farm A (20 kV/66 kV, 21 MW installed), and the other for wind farm B (20 kV/220 kV, 23 MW installed). Additionally, this work proposes the connection of SLBESs downstream from the substation A and B in order to recover electricity from the transmission system operator curtailments orders. The power and capacity of the battery would vary depending on the scenarios detailed in the next section. Moreover, 18 MW of extra wind power and 14 MW of new photovoltaic plants are

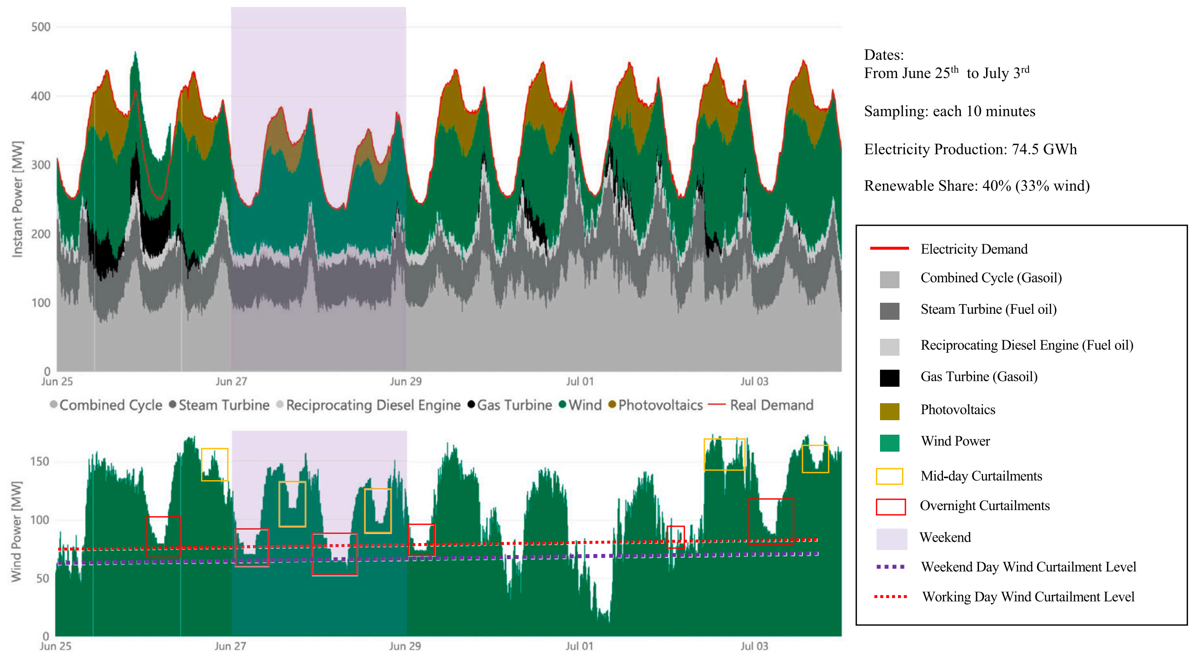


Fig. 1. Tenerife electricity generation by technologies (end of June – firsts of July 2020) and Wind power curtailments. *Source:* Red Eléctrica de España. Real-time production by technologies (2020).

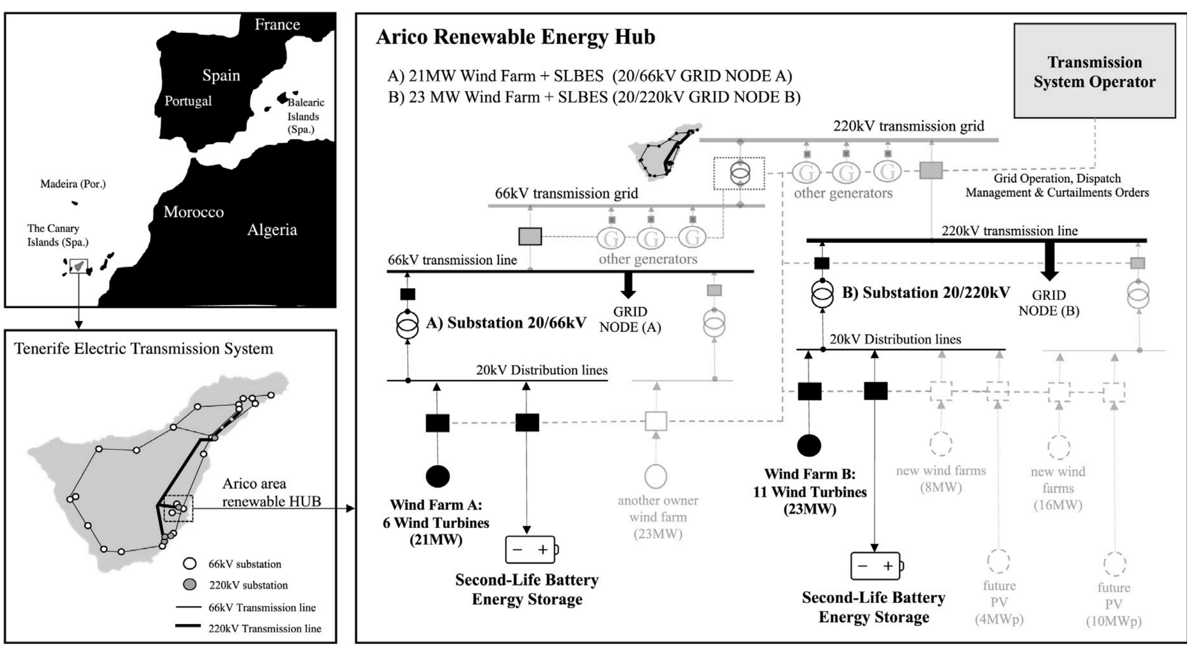


Fig. 2. Case study connection scheme.

expected to be connected to the 20/220 kV substations in the short-term. The integration of this new plants on our grid nodes and the renewable growth expectation in the island for the next 20 years make critical the curtailment's medium-term scenario.

4. Methodology

Fig. 3 shows the methodology proposed to perform the techno-economical analysis of the use of second-life batteries to recover electricity from renewable surplus. The methodology comprises two main parts: technical assessment and economic assessment.

4.1. Technical assessment: Electric vehicle market, surplus energy from wind farms and second-life battery scenarios

The first step in the technical assessment was to analyze the current status of EV market in the region, and forecast the number of sales in a medium-term scenario (up to 2031). This forecast relies on the compilation of the global vehicle sales, EV sales and the battery sizes of each model sold from 2010 to 2020 (Dirección General de Tráfico, 2020). We projected future global sales by using a 10-year horizon moving average, as expressed in:

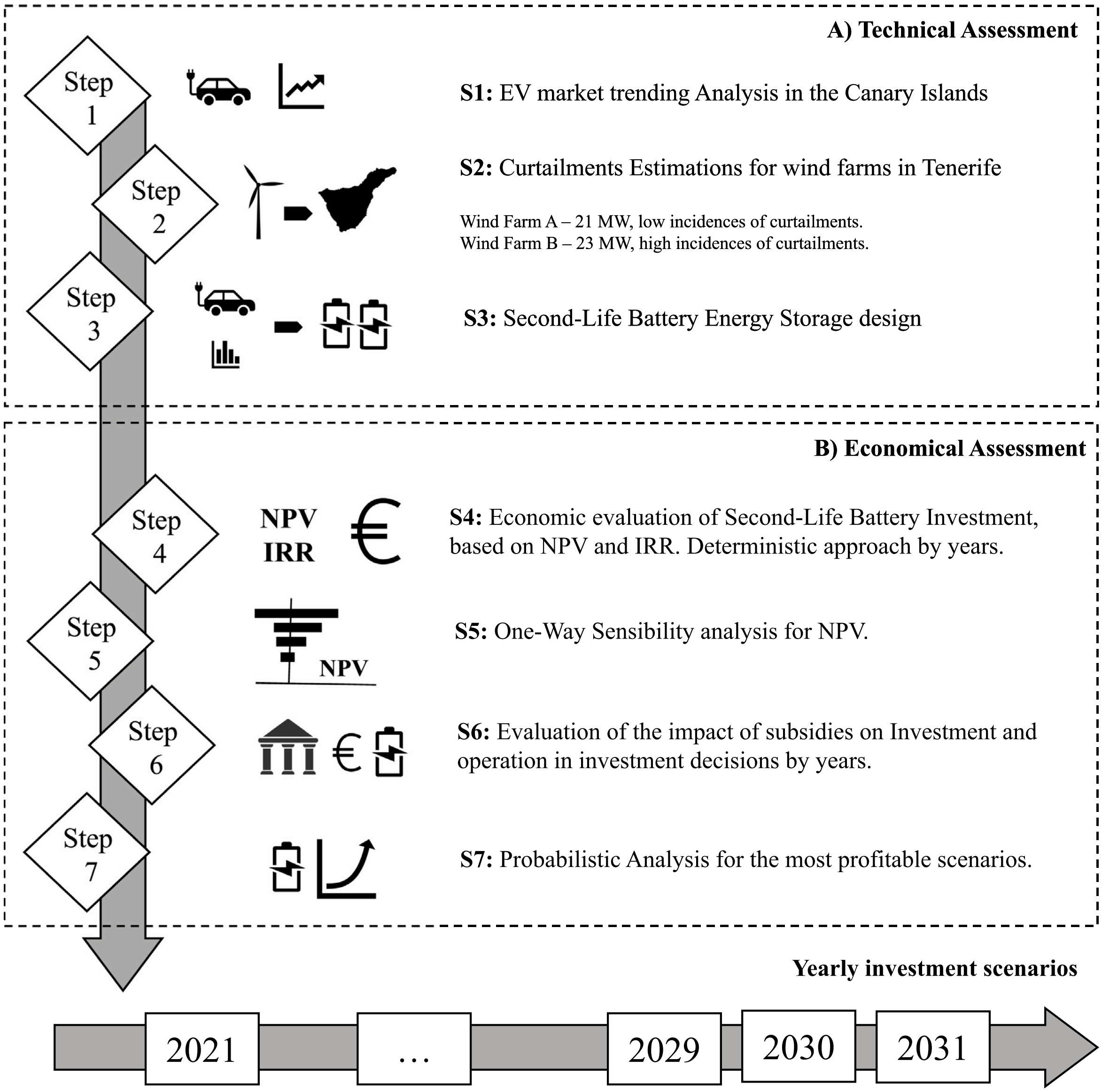


Fig. 3. Methodology scheme.

$$V_T(y) = \sum_{i=y-11}^{y-1} V_T(i)/10 \tag{1}$$

where $V_T(y)$ is the vehicle sales at year y.

In order to obtain the growth of the fleet of electric vehicles from which we will take second-hand batteries, we estimated an average scenario between two different forecasts: conservative and optimistic. The conservative forecast projected the future sales of EV by adjusting a polynomial function from the brute EV sales during the collected period (2010–2020). This estimation is expressed by:

$$\begin{aligned} V_{E,CON}(y) = {} & 2.1982 \times (y - 2009)^3 \\ & - 24.07 \times (y - 2009)^2 \\ & + 60.927 \times (y - 2009) \end{aligned} \tag{2}$$

where $V_{E,CON}(y)$ is the EV sales at year y.

Analogously, the total battery capacity trend ($Cap_{EV}(y)$) from EVs was computed by using a polynomial function:

$$\begin{aligned} Cap_{EV}(y) = {} & 0.1635 \times (y - 2009)^3 \\ & - 2.1395 \times (y - 2009)^2 \\ & + 8.1509 \times (y - 2009) - 7.6584 \end{aligned} \tag{3}$$

where $Cap_{EV}(y)$ is measured in MWh.

Conversely, the optimistic forecast relied on the relative (instead of absolute) growth of EV sales ($\Delta V_E(y)$), expressed by:

$$\begin{aligned} \Delta V_E(y) = {} & MIN(0.0002 \times (y - 2010)^3 \\ & - 0.0026 \times (y - 2010)^2 \\ & + 0.0088 \times (y - 2010) - 0.0069, 1) \end{aligned} \tag{4}$$

Hence, the absolute yearly EV sales for the optimistic approach can be computed as $V_{E,OPT}(y) = \Delta V_E(y) \times V_T(y)$. We obtained the total accumulated battery capacity from EVs per year ($Batt_{Avail}(y)$) by using the battery growth rate per average vehicle ($V_{E,CON}(y)/Cap_{EV}(y)$), and an average EV fleet between conservative and optimistic scenarios ($V_E(y) = (V_{E,CON}(y) + V_{E,OPT}(y))/2$).

Starting from the estimations on EV sale trends and battery size (from 2021 to 2031), we assumed 10 years of lifespan for the battery use in land transport applications, according to the years, kilometers and battery degradation for the most conservative manufacturers warranty (Wilson, 2021). We have considered an average range of 320 km per deep-cycle (nearly 160,000 km, or 500 cycles at 80% of capacity). Hence, we ensure collected batteries to have enough life to last 7 years as SLBES (over 700 additional cycles). Therefore, the total accumulated vehicles sold from 2015 to 2021 would become the batteries available at the beginning of 2031. The battery availability per year is expressed by:

$$Batt_{Avail}(y) = \sum_{i=y-17}^{y-10} V_E(i) \times Cap_{EV}(i) \tag{5}$$

where $Batt_{Avail}(y)$ is the number of second life batteries available at year y.

Step 2 evaluated the energy surplus from our wind farms. Wind farm A was the most affected by curtailments, reaching a 2.5% of limitation during 2020 (measured as the potential of energy curtailed over the total produced during the year), in contrast to wind farm B which barely reached 1%. According to the estimations of the wind farm owners, validated in Díaz et al. (2015), the increase of curtailments could reach up to 28% on wind farm A and a 45% for wind farm B by 2040. For example, almost a quarter of the potential electricity produced on wind farms would be limited in 20 years horizon if demand-side response and storage measures are not taken at regional level.

$$E_S(y) = MIN(0.5 \times AEP, E_S(y-1) \times (1+C)) \tag{6}$$

where AEP is the average annual energy production, and C is the increase of curtailments.

Step 3 determined the capacity of the SLBES from the results of the previous steps. Several SLBES installation scenarios were proposed for each year (from 2022 to 2031) according to the following technical limitations: (i) the availability of second-life EV batteries, which was defined by the EV market in the region, and the forecast of the number of sales in a medium-term scenario; and (ii) the wind energy surplus from wind farms under study.

For the first conditioner, that is, the availability of batteries, the SOH, the round-trip efficiency, the DOD and a retrofitting factor were applied. The battery degradation factor reflects the loss in storage capacity due to first-life use. Since we have considered 320 km of range for an electric car, the number of depth cycles is nearly 500. Besides, we are assuming lithium nickel-based batteries to be the predominant type for the study period, resulting in nearly 1200 cycles (Preger et al., 2020). The SOH from EV battery application was fixed on 80% of its initial capacity (Zhan et al., 2020; Huang et al., 2019; Martinez-Laserna et al., 2018). Furthermore, the retrofitting factor (P_{Ret}) was set at 60%, i.e., we can only collect, check, transform, and install a fraction of the total batteries on the oldest EV fleet. This is mainly caused by a premature degradation, or the need for grouping by car models with similar batteries The total capacity available from second life batteries at year y is expressed by:

$$Cap_{Avail}(y) = Batt_{Avail}(y) \times P_{Ret} \times SOH \tag{7}$$

where $Batt_{Avail}(y)$ is the number of second life batteries available at year y (Eq. (5)).

Respect operational parameters, the round-trip efficiency was assumed to be 89% (Nadeem et al., 2019; Dehghani-Sanij et al., 2019; Gür, 2018; Aneke and Wang, 2016; Kim et al., 2019; Saini et al., 2020). Finally, to ensure a safe operation, a range from 25% to 95% state-of-charge was applied to prolong the second life of the battery up to 7 years of low-intensity operation conditions. The rate of discharge (C-rate) was limited to below 1C for all scenarios.

For the second condition, the maximum required battery capacity (Cap_{Req}) was obtained according to the surplus energy in extreme conditions (according to operational data of the wind farm owners). We assumed 800 h of limitation per year ($LimitHours$), normally shared in high wind streaks of 7 h ($ConsHours$) maximum (generally distributed during off-peak hours) based on historical data from the wind farm owner.

$$Cap_{Req}(y) = E_S(y) \times ConsHours \times LimitHours \times DOD \tag{8}$$

The capacity finally installed (Cap_{Inst}) was constrained by both the capacity required (Cap_{Req}) and the capacity available (Cap_{Avail}), as expressed by:

$$Cap_{Inst}(y) = MIN\left(Cap_{Req}(y), Cap_{Avail}(y)\right) \tag{9}$$

From this, we were able to derive the percentage use of the battery (Eq. (10)), which, in turn, led to the estimation of the energy injected from batteries (Eq. (11)) and the number of cycles (Eq. (12)).

$$Batt_{Exp}(y) = MIN\left(1, \frac{Cap_{Inst}(y)}{E_S(y) \times ConsHours \times LimitHours}\right) \tag{10}$$

$$E_{Batt}(y) = E_S(y) \times Batt_{Exp}(y) \times BattEff \tag{11}$$

$$N_{Cycles}(y) = \frac{E_{Batt}(y)}{Cap_{Inst}(y)} \tag{12}$$

4.2. Economic assessment

Step 4 of the proposed methodology led to the obtainment of a base case for the economic assessment. For each wind farm and each year within the period 2021–2031, we assumed a maximum initial inversion to fulfill the surplus energy from the wind farm, limited to the estimated availability of second life batteries in Tenerife that year. We computed the annual and cumulative cash flow for 7 years by using the indirect method (Board, 1987). We estimated the income as the factor of the energy injected from the batteries and the marginal sales price of such energy. We subtracted direct operation and management costs, and amortization from the incomes to estimate the Earnings Before Interest and Taxes (EBIT). We applied an estimated tax rate of 7% to calculate the net balance, and added again the depreciation (BOE, 2021c). We used the cash flow to compute both the NPV and IRR, by applying a discount rate of 6% that is commonly used by energy sector investors (BOE, 2021b).

Afterwards, we performed a one-way sensitivity analysis on the most relevant variables that may affect the results for each wind farm at medium- (2027) and long- (2031) term. Table 1 summarizes the values used in the analysis.

An investment was considered profitable when a positive NPV, an IRR over 6% (set by the market regulator and utilities), and a payback under the estimated lifespan of the installation were all obtained. Although our preliminary analyses shown that achieving profitable inversions was suitable even without public funding, we analyzed the impact of two different incentives from the government: on the retrofit cost (Capital Expenditures – CAPEX –); and on the energy injected into the grid (Operational Expenditures – OPEX –). A two-ways sensitivity analysis was performed by considering both subsidies: (1) percentage of subsidy on CAPEX; and (2) a bonus incentive on energy injected to the grid to support the OPEX. We only selected those combinations of subsidies that led to profitable scenarios for both wind farms in order to guarantee uniformity for the proposal of specific policy measures at the island level. After a preliminary analysis, the CAPEX subsidy was assessed from zero to 45% of the total retrofit investment, and the OPEX was evaluated for remuneration for energy injected from zero to 20 €/MWh. The objective of this incentive scheme is to reduce the average overruns that the use of oil-derived fuels for conventional electricity generation causes in the islands.

Finally, we analyzed the robustness of the selected subsidized scenarios by performing both one-way and probabilistic sensitivity analyses (Step 7 from Fig. 3). The latter (probabilistic sensitivity analysis – PSA –) consisted on performing 5000 Montecarlo simulations by varying the main parameters according to the uncertainty surrounding their estimate value (see Table 1). We estimated the probability for each scenario to be feasible by accounting for the proportion of simulations that were profitable.

Table 1
Most relevant parameter values for the base case, one-way sensitivity analysis and probabilistic sensitivity analysis.

Parameter	Base case	One-way[a]	Probabilistic[b]	Source[c]
Second-Life battery retrofitting percentage	60%	40%–80%	UNIFORM(30%; 90%)	Ass.
Battery efficiency	89%	80%–95%	BETA(89%; 3%)	Nadeem et al. (2019) and Díaz et al. (2015)
Average battery degradation (SOH) from EVs	80%	60%–95%	BETA(80%; 5%)	Saez-De-Ibarra et al. (2016)
DOD availability	70%	60%–85%	BETA(70%; 5%)	Saez-De-Ibarra et al. (2016)
Cost of operation & management (in €/MWh year)	1800	1600–2000	UNIFORM(1600; 2000)	LAZARD (2019)
Lifespan of first life batteries (in years)	10	8–15	UNIFORM(8; 12)	Wilson (2021) and Preger et al. (2020)
Lifespan of second life batteries (in years)	7	6–10	UNIFORM(6; 8)	Wilson (2021) and Preger et al. (2020)
Growth rate on surplus energy for WF A	30%	24%–36%	UNIFORM(24%; 36%)	Ass.
Growth rate on surplus energy for WF B	15%	12%–18%	UNIFORM(12%; 18%)	Ass.
Average annual electricity production in WF A (in MWh)	58,800	54,800–62,800	NORMAL(58,800; 2940)	WF
Average annual electricity production in WF B (in MWh)	64,400	60,400–68,400	NORMAL(64,400; 3220)	WF
Energy surplus in the base year in WF A (in MWh)	88			WF
Energy surplus in the base year in WF B (in MWh)	1760			WF
Relationship between electricity prices and opportunity cost	36%	10%–50%	UNIFORM(26%; 46%)	Ass.
Tax rate on electricity production	7%	0%–10%		BOE (2021c)
Discount rate	6%	3%–9%		BOE (2021b)
Average market price of electricity (in €/MWh)	194	50–225	GAMMA(194; 64)	Operador del Mercado Ibérico de Energía (2022)
Retrofit cost factor	1	0.75–1.25	UNIFORM(0.75; 1.25)	Sun et al. (2018)
Growth rate on market sale price of electricity	−2.5%	−3%–1%	NORMAL(−2.5%; 1.5%)	Ass.
Yearly curtailments (in hours)	800	700–1200	NORMAL(800; 200)	WF
Consecutive curtailments (in hours)	7	5–8	NORMAL(7; 2)	WF

DOD: Depth of Discharge; EV: Electric Vehicle; SOH: State of Health.
[a]Lower and upper values used in the one-way sensitivity analysis.
[b]Probability distribution and parameters. Lower and upper limits for uniform distribution; average and standard deviation for the rest of distributions.
[c]Ass. - Assumption; WF - Wind farm owner database.

5. Results and discussion

Table 2 details the results of the technical assessment. The first rows show the potential batteries that could provide 10 years-old and older EVs (Eq. (5)). The available capacity for second-life batteries are 52% below this figures, because of the restriction of 60% retrofitting factor and at 80% of state of health due to aging (calculated from Eq. (7)). Despite these limitations, we estimate that it is possible to collect up to 83.2 MWh of second-life batteries by 2031.

Our estimations show fewer curtailments for wind farm A when compared to wind farm B. At the end of the studied period, the potential energy surplus that could be stored would be around 8188 MWh for wind farm B, which represents more than 20% of the total energy injected directly from wind turbines in an average year. Conversely, curtailments represent just a 6.7% of total energy injected for wind farm A (according to Eq. (6)).

From 2022 to 2024, the capacity of batteries in both wind farms is narrowed by the scarcity of available second-life batteries. Thus, we could not recover totally from the energy spills with the batteries. From 2029, the expected growth of the EV market would be able to fulfill the curtailments of either wind farm, and thus would be the determinant factor for the battery total capacity. The results were computed following Eqs. (8) and (9), and are described in step 3 (Table 2). Additionally, Eqs. (10) and (12) evaluated the average power curtailed and the total number of cycles of the battery during the second-lifetime period, respectively.

The CAPEX of second-life battery retrofitting is calculated from useful second-life battery energy storage (first row of step 3 in Table 2), and from the retrofitting cost (Sun et al., 2018) (last row of Table 2).

Finally, the average market price is computed by using a base value of 193.88 €/MWh, which varies year by year proportionally to the evolution of the market sale price (Table 1). The marginal sale price of electricity injected from the battery to the grid is the difference between the average electricity market price and the purchase price of the electricity from our wind farms (represented by the opportunity cost of electricity).

Fig. 4 shows the economic feasibility of SLBES by year of installation and wind farm, in terms of NPV (a) and IRR (b). Investment in any of the wind farms is not profitable until 2025. Beyond that time horizon, NPV grows smoothly for wind farm A, and exponentially for wind farm B. As for IRR, it tends to increase linearly up to 2027, when it reaches a value about 10% for both wind farms. The same trend applies to wind farm B until 2030 when it seems to flatten at around 14%. The limited capacity available on SLBES stands as the major constraint for the profitability of the investments, and may drive investors to delay the investment. However, they should be aware that long term predictions are subject to a higher uncertainty, as discussed below.

The results of the one-way sensitivity analysis on the NPV are illustrated by means of tornado diagrams for each wind farm and two different years (Fig. 5). Each diagram shows the five most relevant variables for each scenario. For both, medium- (Figs. 5(a) and 5(b)) and long- (Figs. 5(c) and 5(d)) term analyses, the relative impact of the different parameters is very similar. Nevertheless, wind farm B shows much more pronounced differences with respect to the base value for every parameter due to its larger SLBES capacity.

Variations in the average electricity market price notably affect the expected economic result. A pre-2021 price level (around 50 €/MWh) would lead to unfeasible investment scenarios in the absence of public funding. The relationship between this price and the wind farm base price, together with the growth rate on the electricity market price, also notably affect the expected results at medium- and long- term. The former may lead to unfeasible investment scenarios as it reach higher levels, hence reducing the margin of benefits. Such elevated levels for this parameter represent scenarios where the opportunity cost derived from alternative technologies (such as hydrogen) is high. The latter, i.e., the growth rate of the market price, would not lead to negative NPVs even for a 3% yearly reduction. An increment in the retrofitting cost factor may lead to an unfeasible investment scenario in the medium-term for wind farm A, but not in any other scenario. Variations in any other parameter may reduce or increase the benefit, but would not change the potential feasibility of the scenarios. These parameters are the discount rate, the battery efficiency, the tax rate and the lifespan of 1st life batteries.

After analyzing the impact of CAPEX and OPEX subsidies (see full details on two-way sensitivity analysis in the Appendix A, Table A.1 of the supplementary material), none of the scenarios required OPEX to become profitable due to the current electricity prices. Besides, at medium- and long-term, and even with no CAPEX, all scenarios become profitable. We analyzed in detail four scenarios with no OPEX: two at medium-term (2027), with 0 and 15% CAPEX, and two at long-term (2031), with 0 and 15% CAPEX (see Table 3).

Table 2
Results of technical assessment for second-life battery design.

	Wind farm	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Step 1: EV market trending analysis in the Canary Islands											
Potential batteries from EV fleet (MWh)	–	0.39	0.88	2.16	3.43	5.76	9.39	17.89	41.19	82.43	173.40
Second-life available battery capacity (MWh)	–	0.19	0.42	1.04	1.65	2.77	4.51	8.59	19.77	39.57	83.23
Step 2: Curtailments estimations for wind farms in Tenerife											
Energy curtailments (MWh)	A	2615	3399	4419	5745	7468	9709	12,622	16,408	21,331	27,730
	B	25,759	29,623	34,066	39,176	45,053	51,811	59,582	68,520	78,798	90,617
Average curtailments respect total energy injected (%)	A	0.6%	0.8%	1.1%	1.4%	1.8%	2.4%	3.1%	4.0%	5.2%	6.7%
	B	5.7%	6.6%	7.6%	8.7%	10.0%	11.5%	13.2%	15.2%	17.5%	20.1%
Average power curtailed (MW)	A	0.47	0.61	0.79	1.03	1.33	1.73	2.25	2.93	3.81	4.95
	B	4.60	5.29	6.08	7.00	8.05	9.25	10.64	12.24	14.07	16.18
Step 3: Second-life battery energy storage design and sizing											
Useful Second-life battery energy storage (MWh)	A	1.9	2.4	3.1	4.1	5.3	6.9	9.0	11.7	15.2	19.7
	B	29.1	33.5	38.5	44.2	50.9	58.5	67.3	77.4	89.0	102.4
Energy injected from batteries (MWh)	A	1714	2525	3562	4860	6517	8608	11,233	14,603	18,984	24,680
	B	7921	13,326	19,496	26,502	34,424	43,189	52,261	60,983	70,130	80,649
Number of depth cycles during second-life use	A	712	712	712	712	712	712	521	498	498	498
	B	712	712	712	712	712	712	712	498	498	498
CAPEX of second-life batteries retrofitting (€)	A	14,428	28,811	64,064	92,014	140,450	208,873	364,732	456,420	549,113	663,856
	B	79,135	112,809	170,819	251,899	435,981	916,157	1,680,896	3,028,202	3,222,821	3,446,700
Other relevant variables											
Average market price (€/MWh)	–	184.3	179.7	175.2	170.8	166.6	162.4	158.3	154.4	150.5	146.8
Marginal sale price (€/MWh)	–	122.7	119.6	116.7	113.7	110.9	108.1	105.4	102.8	100.2	97.7
Retrofitting cost (€/MWh)	–	76.3	68.5	61.8	55.9	50.8	46.3	42.5	39.1	36.2	33.7

- Medium-term (year 2027), no CAPEX scenario. Both wind farms achieve an IRR around 10%, with a return of investment relatively close to the expected lifespan of the installation (5.9 years). According to the PSA, the probabilities of wind farm A and wind farm B to be profitable under these conditions are 57% and 60%, respectively. The uncertainty on the estimations of the average market price explains more than 50 and 30%, respectively for wind farms A and B, of the uncertainty upon these results.
- Medium-term with 15% CAPEX scenario. In this case, both wind-farms achieve an IRR above 14%, and see the payback reduced to 5.0 years. The probability of the investments to be profitable increases to 68% and 72%, for wind farm A and B, respectively.
- Long-term (2031), no CAPEX scenario. While wind farm A achieves an IRR of 12.6% for a NPV of about 223,500 €, wind farm B obtains 11.7% for a NPV of above 1,000,000 €. The payback, in both cases, is below 5.7 years. The probabilistic analysis shows that this scenario is profitable for wind farm A in 67% of cases; 70% when wind farm B is analyzed. Again, the parameters that characterize the market price are the main drivers for such uncertainty.
- Long-term, 15% CAPEX scenario. Actually, this scenario would be unfeasible, since the IRR is above the CAPEX for both wind farms (16.8% and 15.8%, respectively), and thus, would not be subject to public funding. The payback would be below 5 years for both wind farms. The confidence on the profitability of the investment would increase to 76 and 78%, respectively, for wind farm A and B.

Appendix B of the supplementary material shows further detail on these results.

This study has potential limitations:

(i) The case study is limited to two wind farms on an isolated system (Tenerife). In order to extend the study to the whole region, we would require accurate data on energy production and curtailment for every wind farm on the island. Although the company that owns and operates the wind farms chosen for the case study provided us with this data, there is no public data set in the studied region that details such information for every wind farm. In any case, the chosen wind farms produce around 23% of the installed wind power in the island, and thus represent a significant part of the total production.

(ii) The growth of the EV sales could represent a quantitative leap in the available capacity of batteries. According to our EV fleet projections in the Canary Islands, by 2040 there would be a total of 37 GWh of battery capacity on 990,320 EVs, while nearly 6.2 GWh could be susceptible to being exploited as SLBES. We assessed three different sales scenarios to deal with the uncertainty surrounding the expected trend on EV sales: even the most conservative scenario ended with batteries enough to fulfill the requirements of the chosen wind farms.

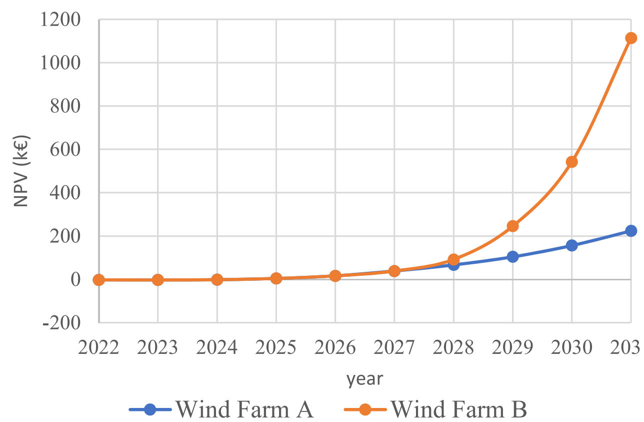
(iii) Another parameter subject to high uncertainty is the projection in terms of the technological improvement of battery packs and new chemistry. We assumed that NCA and NMC batteries will predominate, with life cycles that can extend the first-life usage, on average, up to 10 years (about 160,000 km during the period and degradation of 80% of the SOH); with a second life of seven more years. However, lithium iron phosphate (LFP) batteries are gaining relevance today due to their lower dependence on price volatility of raw materials (dispense with cobalt or nickel, and requires less lithium). During the last year the price of a kWh of batteries has risen from 118–128 $/kWh (May 2021), by 41% for NMC and 32% for NCA and 29% for LFP (Krishna, 2022). Today, LFPs just represent 4% of the total EV market. However, this technology is key to further boosting EV deployment because of their less use of lithium and unused of cobalt and nickel. This technology would make our scenarios even more profitable due to the extension of their lifespan (between 1,500 to 6,000 cycles) (Preger et al., 2020).

(iv) Retrofit has multiple difficulties such as compatibility between battery packs from different chemistry and manufacturers, monitoring of their cooling and safety issues. The uncertainty in

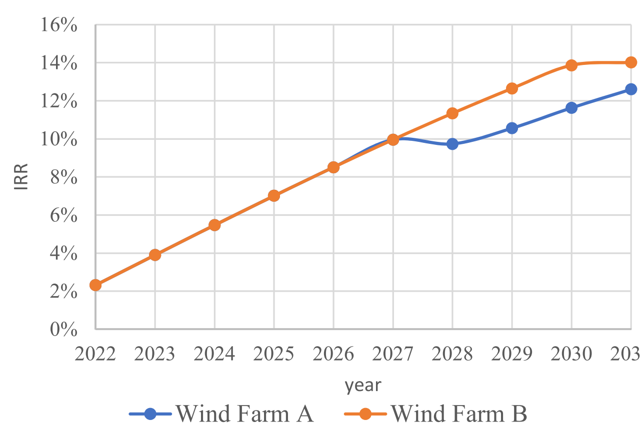
Table 3
Profitable scenarios subsidy schemes and costs.

Inv. year	CAPEX (%)	Wind farm A			Wind farm B		
		IRR (%)	CAPEX (€)	Avg. Subsidy (€/MWh)	IRR (%)	CAPEX (€)	Avg. Subsidy (€/MWh)
2027	0%	9.96%	0	0.00	9.96%	0	0.00
2027	15%	14.15%	31,331	3.64	14.15%	137,424	3.18
2031	0%	12.60%	0	0.00	11.73%	0	0.00
2031	15%	16.78%	99,578	4.03	15.75%	517,005	6.41

Avg. Subsidy: Average Subsidy; CAPEX: Capital Expenditures; Inv. year: Investment year; OPEX: Operational Expenditures.

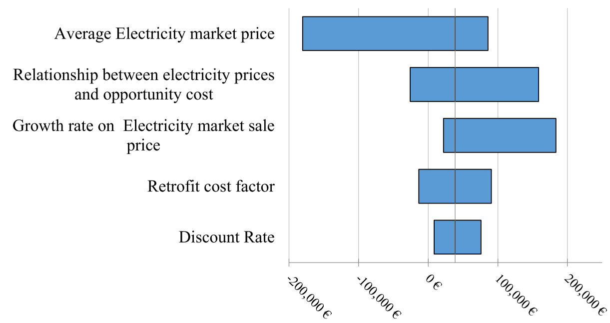


(a) NPV for Second-life Batteries Energy Storage

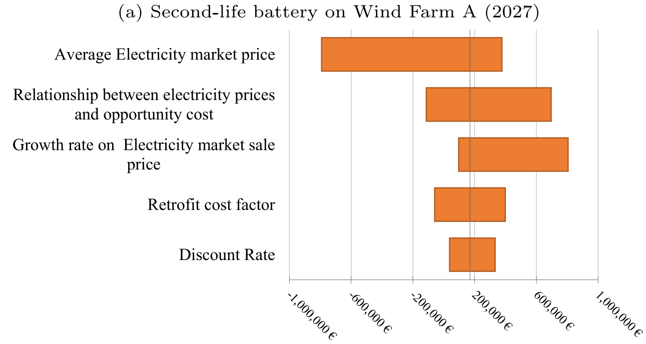


(b) IRR for Second-life Batteries Energy Storage

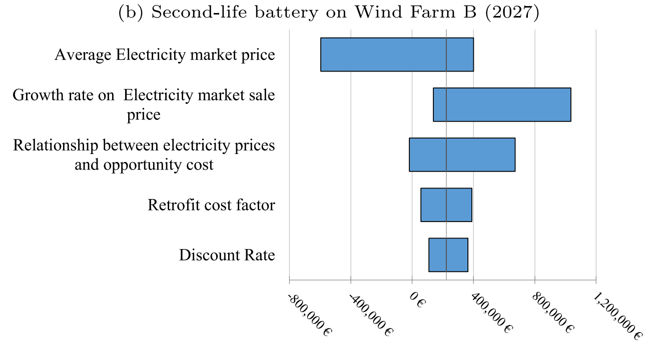
Fig. 4. Economic evaluation of second-life battery energy storage.



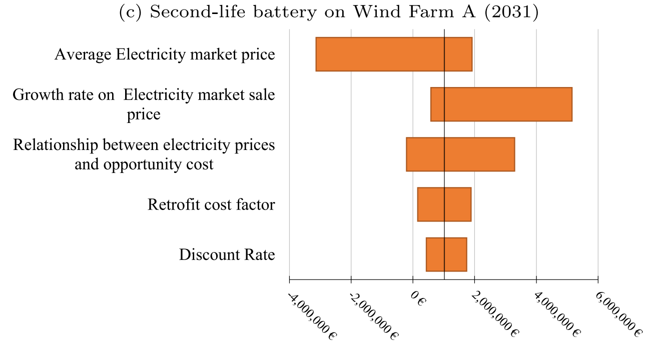
(a) Second-life battery on Wind Farm A (2027)



(b) Second-life battery on Wind Farm B (2027)



(c) Second-life battery on Wind Farm A (2031)



(d) Second-life battery on Wind Farm B (2031)

Fig. 5. One-way sensitivity analysis.

retrofit costs and the decrease in the price of new batteries could make investors prefer to install new instead of recovering old ones. We established a conservative 60% retrofitting factor to consider that only that proportion of vehicles will be suitable for making up a container of batteries of at least 1 MWh (composed of batteries of the same vehicle model). As derived from the one-way sensitivity analysis, even reducing this percentage to 40% would not change the profitability of the chosen scenarios. The study has been limited to EV batteries from the islands to promote a circular economy in the archipelago, discouraging the possibility of importing used batteries from the European continent.

(v) The behavior of the electricity market has suffered drastic changes in a short period, with the average price of electricity increasing from 50 to 192 €/MWh in around a year (Operador del Mercado Ibérico de Energía, 2022). Geopolitical tension and its impact on the fossil fuel market (especially on natural gas) can be pointed out as the main drivers for this change. Although the current scenario, with high prices, benefits the profitability of investments such as the one assessed in this article, there is a high uncertainty on the future behavior of the market. According to our sensitivity analyses, returning to pre-2021 prices would require public funding (both in terms of OPEX and CAPEX) to make this kind of investments profitable.

(vi) The uncertainty on the future trend of the electricity market also affects the purchase price of surplus energy. This price may rise, given that its opportunity cost will depend on multiple storage alternatives and alternative uses. Battery energy storage, green hydrogen by electrolysis, liquid-air storage, or demand response could be competitors to purchase these energy spills at a lower price than electricity prices (Ferrario et al., 2020; Ramirez-Diaz et al., 2016; Legrand et al., 2019). In advance, the SLBES starts with an advantage because its CAPEX is lower than first-life batteries. SLBES also outperforms the round-trip efficiency of hydrogen production or air-liquid. Consumption associated with demand response may be more competitive, although it would require the availability of manageable consumption within a short distance of wind farms. Finally, we have addressed this issue on the one-way sensitivity analysis that shows an unprofitable scenario when the acquisition price of electricity represents more than half of the market price.

Once the limitations faced by the work have been addressed and exposed, we must indicate that we have carried out various sensitivity studies with multiple scenarios for all the parameters mentioned above.

As a final remark, and beyond the economic benefits of using second-life batteries as large-scale ESS, the use of this technology becomes in other gains: (i) system emissions would be reduced and the renewable resource exploited almost entirely (solving energy spills); (ii) the inclusion of other energy storage with greater impact on the environment would be reduced; (iii) batteries would provide specific services to the electrical grid, from those derived from quick response services to massive energy coverage at peak power demand; (iv) hundreds of tons of batteries would be reused, extending their useful life for at least 10 more years. (v) a circular economy based on lithium and other high-value raw materials for Canary Island would be created, hence diversifying the economy of the region.

6. Conclusion and policy implications

This article explored the potential of SLBES to support a greater integration of renewable energies. Specifically, we studied the use of SLBES with two different wind farms, with the aim of increasing the robustness of the Tenerife isolated electrical systems. To cope with this aim, we performed a techno-economical assessment to evaluate the feasibility of a SLBES under different scenarios.

Our main results reveal that, under the current remuneration framework and market electricity prices, investment in SLBES is feasible. To achieve economic viability, it is not necessary to subsidize CAPEX or OPEX. As the number of available batteries from EVs grows, investment scenarios become feasible, with the best results obtained after 2027. The viability of the SLBES plans depends highly on how the electricity market will evolve for the next decade. The current energy crisis favors the development of new energy storage alternatives plus renewable to substitute fossil fuel backup technologies. However, a fall in the electricity prices scenario till pre-2021 figures will require political efforts to provide economic support to SLBES, specifically in CAPEX.

Policymakers should assess both other similar solutions for ESS and the risk of inaction in terms of accumulated battery residuals in controlled landfills. Currently, the existing alternatives for energy storage present both advantages and disadvantages. For example, although pumped-hydro energy storage provides large useful life and maturity, it requires a large investment, availability of adequate areas for the reservoirs, investment in desalinization equipment and global energy losses (Ramirez-Diaz et al., 2016; ENDESA and Monitor Deloitte, 2020; Garcia Latorre et al., 2019; Ramos-Real et al., 2018). Green hydrogen production from renewable surplus as ESS could provide multiple end-use applications. For example, green hydrogen could be exploited in heavy-duty transportation and electricity sector (through fuel cells). Moreover, hydrogen could be burned and used as heat source, usually in industry applications, maritime and air transportation, and also conventional power plants to produce electricity. Nonetheless, the high cost of hydrogen infrastructure, and the low maturity and poor round-trip efficiency are the main barriers for this technology (ENDESA and Monitor Deloitte, 2020; Gils and Simon, 2017; NREL and U.S. Department of Energy, 2020).

The installation of new stationary Lithium-ion battery storage seems to be a similar solution from a technical point of view in comparison with SLBES. The round-trip efficiency, and low occupation and exploitation of the territory are some of its main advantages. Besides, the cost of lithium-ion batteries is dropping year by year, and this solution starts to be a feasible alternative from an economical perspective (NREL and U.S. Department of Energy, 2020). However, supply-chain of lithium, geopolitics and the priority usage in transportation sector are the biggest obstacles to develop ESS based on lithium stationary batteries.

In any case, taking advantage of batteries from second-life transportation usage poses an opportunity to be explored. The main advantage of extending the lifespan of batteries, as proposed in this study, is the reduction of investment on new batteries. Moreover, from an environmental point of view, the installation of SLBES for 2031 could avoid approximately 0.7 to 1.2 kilotons of accumulated waste (150–260 Wh/kg for NCA and NMC) up to 2031. Furthermore, a potential of 28–90 kilotons of CO2 is saved, derived from the renewable energy stored and injected (from both wind farms) into the electricity grid in substitution of conventional technologies, such as open-cycle turbines fueled by diesel gas (1.12 t.CO2/MWh) (Red Eléctrica de España, 2020). Furthermore, the reduction of the cost for recycling batteries in the Canary islands would be nearly 5 to 7 million euros by 2030 (assuming 1130 €/tonne) (Jo and Myung, 2019). For this reason, the promotion of second-life batteries should be mandatory to avoid the uncontrolled accumulation of these residuals.

As with other types of storage, government support is key to the development of SLBES. Although the current electricity market prices depicts a very favorable scenario to investment on SLBES, this situation may change drastically in the future. Hence, support from the policy makers may reduce the impact of this uncertainty on future investments. In the specific context of Spain, the Government should support the use of second-life batteries, not only because it is a technology that improves the integration of renewable energies in the electrical system, but also since it fits both into the Spanish Circular Economy Strategy and the New EU Regulatory Framework for Batteries goals (Gobierno de España, 2020; European Parliament, 2021).

In conclusion, this work has demonstrated that SLBES is a techno-economical feasible solution to improve the penetration of renewable energy from wind farms in isolated systems. At current electricity prices, government subsidies are not essential. Although, a 15% on government support in CAPEX could guarantee a high probability of success in a wide range of cases ensuring the project's viability. Hence, SLBES arises as a solution of interest to cope with the decarbonization goals in isolated systems

Further research may aim at other potential uses of second-life batteries, such as their integration in smart-grids or self-consumption installations, analyzing both techno-economical and a life-cycle analysis. In addition, a deeper analysis between SLBES and other storage alternatives focused on insular regions would be interesting to provide empirical data energy policy actions. Finally, we encourage the development of a living-lab project in the short term with SLBES in Tenerife.

CRediT authorship contribution statement

A.I. López: Conceptualization, Methodology, Formal analysis, Software, Writing – original draft. **A. Ramírez-Díaz:** Conceptualization, Methodology, Data curation, Formal analysis, Software, Writing – original draft. **I. Castilla-Rodríguez:** Methodology, Data curation, Formal analysis, Software, Writing – original draft. **J. Gurriarán:** Validation, Investigation, Writing – review & editing. **J.A. Mendez-Perez:** Supervision, Funding acquisition, Conceptualization, Methodology, Validation, Writing – original draft.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.enpol.2022.113373.

References

Akram, U., Nadarajah, M., Shah, R., Milano, F., 2020. A review on rapid responsive energy storage technologies for frequency regulation in modern power systems. Renew. Sustain. Energy Rev. 120 (October 2019), 109626. http://dx.doi.org/10.1016/j.rser.2019.109626.

Aneke, M., Wang, M., 2016. Energy storage technologies and real life applications – A state of the art review. Appl. Energy 179, 350–377. http://dx.doi.org/10.1016/j.apenergy.2016.06.097.

Board, F.A.S., 1987. Statement of Financial Accounting Standards No. 95. Technical Report, Financial Accounting Foundation, p. 66, URL: https://www.fasb.org/jsp/FASB/Document_C/DocumentPage?cid=1218220128261&acceptedDisclaimer=true.

BOE, 2021a. Ley 7/2021, de 20 de mayo, de cambio climático y transición energética. In: Boletín Oficial del Estado. pp. 26798–26800.

BOE, 2021b. Real decreto-ley 17/2019, de 22 de noviembre, por el que se adoptan medidas urgentes para la necesaria adaptación de parámetros retributivos que afectan al sistema eléctrico y por el que se da respuesta al proceso de cese de actividad de centrales térmica. pp. 26798–26800, URL: https://www.boe.es/buscar/doc.php?id=BOE-A-2019-16862.

BOE, 2021c. Resolución de 19 de septiembre de 2020, de la dirección general de política energética y minas, por la que se aprueba la cuantía definitiva de los costes de generación de liquidación y del extracoste de la actividad de producción en los territorios no pen. pp. 26798–26800, URL: https://www.boe.es/diario_boe/txt.php?id=BOE-A-2020-11586.

Bonafè, S., 2020. On the proposal for a regulation of the European Parliament and of the Council Regulation concerning batteries and waste batteries. p. 122, URL: https://www.europarl.europa.eu/doceo/document/ENVI-PR-696435_EN.pdf.

D'amico, G., Petroni, F., Vergine, S., 2021. An analysis of a storage system for a wind farm with ramp-rate limitation. Energies 14 (13), 1–25. http://dx.doi.org/10.3390/en14134066.

Dehghani-Sanij, A.R., Tharumalingam, E., Dusseault, M.B., Fraser, R., 2019. Study of energy storage systems and environmental challenges of batteries. Renew. Sustain. Energy Rev. 104 (November 2018), 192–208. http://dx.doi.org/10.1016/j.rser.2019.01.023.

Díaz, A.R., Ramos-Real, F.J., Marrero, G.A., Perez, Y., 2015. Impact of electric vehicles as distributed energy storage in isolated systems: The case of tenerife. Sustainability (Switzerland) 7, 15152–15178. http://dx.doi.org/10.3390/su71115152, URL: https://www.mdpi.com/2071-1050/7/11/15152.

Dirección General de Tráfico, 2020. Portal estadístico. Matriculaciones 2010–2020.

Dui, X., Zhu, G., Yao, L., 2018. Two-stage optimization of battery energy storage capacity to decrease wind power curtailment in grid-connected wind farms. IEEE Trans. Power Syst. 33 (3), 3296–3305. http://dx.doi.org/10.1109/TPWRS.2017.2779134.

ENDESA, Monitor Deloitte, 2020. Los Territorios No Peninsulares 100% Descarbonizados en 2040: La Vanguardia de la Transición Energética en España. Technical Report, ENDESA, p. 104, URL: https://www2.deloitte.com/es/es/pages/strategy/articles/territorios-no-peninsulares-descarbonizados-2040.html.

Engel, H., Hertzke, P., Siccardo, G., 2019. Second-Life EV Batteries: The Newest Value Pool in Energy Storage. Technical Report, McKinsey & Company, p. 5, URL: https://www.mckinsey.com/~/media/mckinsey/industries/automotiveandassembly/ourinsights/secondlifeevbatteriesthenewestvaluepoolinenergystorage/second-life-ev-batteries-the-newest-value-pool-in-energy-storage.pdf?shouldIndex=false.

European Commission, 2019. The European green deal. http://dx.doi.org/10.2307/j.ctvd1c6zh.7, URL: https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf.

European Commission, 2020a. Circular economy action plan. p. 28. http://dx.doi.org/10.2775/855540.

European Commission, 2020b. Sustainable & Smart Mobility Strategy. Technical Report, European Commission, Brussels, p. 26, URL: https://ec.europa.eu/transport/sites/default/files/2021-mobility-strategy-and-action-plan.pdf.

European Parliament, 2021. New EU Regulatory Framework for Batteries - Setting Sustainability Requirements. Technical Report July, European Commission, URL: https://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_BRI(2021)689337.

Ferrario, A.M., Amoruso, C., Robles, R.V., Del Zotto, L., Bocci, E., Comodi, G., 2020. Power-to-Gas from curtailed RES electricity in Spain: Potential and applications. In: Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2020. Institute of Electrical and Electronics Engineers Inc., http://dx.doi.org/10.1109/EEEIC/ICPSEUROPE49358.2020.9160820.

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

Ghasemi, A., Mortazavi, S.S., Mashhour, E., 2016. Hourly demand response and battery energy storage for imbalance reduction of smart distribution company embedded with electric vehicles and wind farms. Renew. Energy 85, 124–136. http://dx.doi.org/10.1016/j.renene.2015.06.018.

Gils, H.C., Simon, S., 2017. Carbon neutral archipelago – 100% renewable energy supply for the Canary Islands. Appl. Energy 188, 342–355. http://dx.doi.org/10.1016/j.apenergy.2016.12.023.

Gobierno de Canarias, 2020. Anuario del Sector Eléctrico de Canarias 2019. Technical Report, Gobierno de Canarias, p. 155, URL: https://www.gobiernodecanarias.org/energia/publicaciones/.

Gobierno de España, 2020. España Circular 2030. Estrategia Española de Economía Circular. Technical Report, Gobierno de España, pp. 1–65, URL: https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/economia-circular/espanacircular2030_def1_tcm30-509532.PDF.

González-Rivera, E., Sarrias-Mena, R., García-Triviño, P., Fernández-Ramírez, L.M., 2020. Predictive energy management for a wind turbine with hybrid energy storage system. Int. J. Energy Res. 44 (3), 2316–2331. http://dx.doi.org/10.1002/er.5082.

Gür, T.M., 2018. Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage. Energy Environ. Sci. 11 (10), 2696–2767. http://dx.doi.org/10.1039/c8ee01419a.

Hossain, E., Murtaugh, D., Mody, J., Faruque, H.M.R., Sunny, M.S., Mohammad, N., 2019. A comprehensive review on second-life batteries: Current state, manufacturing considerations, applications, impacts, barriers & potential solutions, business strategies, and policies. IEEE Access 07, 73215–73252. http://dx.doi.org/10.1109/ACCESS.2019.2917859.

Houache, M.S.E., Yim, C.-H., Karkar, Z., Abu-Lebdeh, Y., 2022. On the current and future outlook of battery chemistries for electric vehicles—Mini review. Batteries 8 (7), 70. http://dx.doi.org/10.3390/batteries8070070.

Huang, Z., Xie, Z., Zhang, C., Chan, S.H., Milewski, J., Xie, Y., Yang, Y., Hu, X., 2019. Modeling and multi-objective optimization of a stand-alone PV-hydrogen-retired EV battery hybrid energy system. Energy Convers. Manage. 181 (August 2018), 80–92. http://dx.doi.org/10.1016/j.enconman.2018.11.079.

Instituto Tecnológico de Canarias, 2022. Plam de Transición Energética de Canarias -Borrador. Technical Report, Dirección General de Energía del Gobierno de Canarias, Las Palmas de Gran Canaria, p. 498, URL: https://www.gobiernodecanarias.org/energia/descargas/SDE/Portal/Planificacion/Estrategias/PTECan2030/1_Borrador_PTECan_EdicionV2.pdf.

International Energy Agency, 2022. Global EV Outlook 2021 - Accelerating Ambitions Despite the Pandemic. Technical Report, International Energy Agency, Paris, p. 101, URL: https://www.iea.org/data-and-statistics/charts/global-ev-sales-by-scenario-2020-2030.

International Renewable Energy Agency, 2019. Transforming Small-Island Power Systems, first ed. International Renewable Energy Agency, Abu Dhabi, URL: https://www.irena.org/publications/2019/Jan/Transforming-small-island-power-systems.

IRENA, 2017. Electricity Storage and Renewables: Costs and Markets to 2030. International Renewable Energy Agency, Abu Dhabi.

IRENA, 2019a. Innovation Landscape for a Renewable-Powered Future: Solutions To Integrate Variable Renewables. International Renewable Energy Agency, Abu Dhabi, pp. 1–164.
IRENA, 2019b. Innovation Outlook - Smart Charging for Electric Vehicles. International Renewable Energy Agency, Abu Dhabi, p. 138, URL: https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Innovation_Outlook_EV_smart_charging_2019.pdf.
Jo, C.H., Myung, S.T., 2019. Efficient recycling of valuable resources from discarded lithium-ion batteries. J. Power Sources 426 (January), 259–265. http://dx.doi.org/10.1016/j.jpowsour.2019.04.048.
Kim, T., Song, W., Son, D.Y., Ono, L.K., Qi, Y., 2019. Lithium-ion batteries: outlook on present, future, and hybridized technologies. J. Mater. Chem. A 7 (7), 2942–2964. http://dx.doi.org/10.1039/C8TA10513H.
Krishna, M., 2022. The EV battery chemistry debate just got more complicated. Fastmarkets URL: https://www.fastmarkets.com/insights/the-ev-battery-chemistry-debate-just-got-more-complicated.
LAZARD, 2019. Lazard's Levelized Cost of Storage Analysis - Version 6.0. Technical Report, LAZARD, p. 28. http://dx.doi.org/10.31826/9781463235543-toc, URL: https://www.lazard.com/media/451566/lazards-levelized-cost-of-storage-version-60-vf2.pdf.
Legrand, M., Rodríguez-Antón, L.M., Martinez-Arevalo, C., Gutiérrez-Martín, F., 2019. Integration of liquid air energy storage into the spanish power grid. Energy 187, http://dx.doi.org/10.1016/J.ENERGY.2019.115965.
Li, J., Fu, Y., Li, C., Li, J., Xing, Z., Ma, T., 2021. Improving wind power integration by regenerative electric boiler and battery energy storage device. Int. J. Electr. Power Energy Syst. 131 (May 2020), 107039. http://dx.doi.org/10.1016/j.ijepes.2021.107039.
Martinez-Laserna, E., Sarasketa-Zabala, E., Stroe, D.I., Swierczynski, M., Warnecke, A., Timmermans, J.M., Goutam, S., Rodriguez, P., 2016. Evaluation of lithium-ion battery second life performance and degradation. In: ECCE 2016 - IEEE Energy Conversion Congress and Exposition, Proceedings. IEEE, http://dx.doi.org/10.1109/ECCE.2016.7855090.
Martinez-Laserna, E., Sarasketa-Zabala, E., Villarreal Sarria, I., Stroe, D.I., Swierczynski, M., Warnecke, A., Timmermans, J.M., Goutam, S., Omar, N., Rodriguez, P., 2018. Technical viability of battery second life: A study from the ageing perspective. IEEE Trans. Ind. Appl. 54 (3), 2703–2713. http://dx.doi.org/10.1109/TIA.2018.2801262.
Miao, Y., Hynan, P., Von Jouanne, A., Yokochi, A., 2019. Current li-ion battery technologies in electric vehicles and opportunities for advancements. Energies 12 (6), 1–20. http://dx.doi.org/10.3390/en12061074.
Ministerio de Industria Energía y Turismo, 2015. Real decreto 738/2015, de 31 de julio. URL: https://www.boe.es/boe/dias/2015/08/01/pdfs/BOE-A-2015-8646.pdf.
MITECO, 2020. Plan Nacional Integrado de Energía y Clima 2021–2030. Ministerio Para la Transición Ecológica y El Reto Demográfico, Gobierno de España, p. 25, URL: https://www.miteco.gob.es/es/prensa/pniec.aspx.
Nadeem, F., Hussain, S.M., Tiwari, P.K., Goswami, A.K., Ustun, T.S., 2019. Comparative review of energy storage systems, their roles, and impacts on future power systems. IEEE Access 7, 4555–4585. http://dx.doi.org/10.1109/ACCESS.2018.2888497.
Nguyen, N., Mitra, J., 2016. An analysis of the effects and dependency of wind power penetration on system frequency regulation. IEEE Trans. Sustain. Energy 7 (1), 354–363. http://dx.doi.org/10.1109/TSTE.2015.2496970.
NREL, U.S. Department of Energy, 2020. Energy Storage Grand Challenge: Market Report. Technical Report December, U.S. Department of Energy, URL: https://www.energy.gov/sites/prod/files/2020/12/f81/EnergyStorageGrandChallengeRoadmap.pdf.
Operador del Mercado Ibérico de Energía, 2022. Mínimo, medio y máximo precio de la casación del mercado diario | OMIE. URL: https://www.omie.es/es/market-results/annual/daily-market/daily-prices?scope=annual&year=2022.
Preger, Y., Barkholtz, H.M., Fresquez, A., Campbell, D.L., Juba, B.W., Romàn-Kustas, J., Ferreira, S.R., Chalamala, B., 2020. Degradation of commercial lithium-ion cells as a function of chemistry and cycling conditions. J. Electrochem. Soc. 167 (12), 120532. http://dx.doi.org/10.1149/1945-7111/abae37.
Ramirez-Diaz, A., Ramos-Real, F.J., Marrero, G.A., 2016. Complementarity of electric vehicles and pumped-hydro as energy storage in small isolated energy systems: case of La Palma, Canary Islands. J. Mod. Power Syst. Clean Energy 4 (4), 604–614. http://dx.doi.org/10.1007/s40565-016-0243-2.
Ramos-Real, F., Barrera-Santana, J., Ramírez-Díaz, A., Perez, Y., 2018. Interconnecting isolated electrical systems. The case of Canary Islands. Energy Strategy Rev. 22, http://dx.doi.org/10.1016/j.esr.2018.08.004.
Red Eléctrica de España, 2020. Metodología de cálculo de emisiones de gases de efecto invernadero (GEI) del Grupo Red Eléctrica. URL: https://www.ree.es/sites/default/files/04_SOSTENIBILIDAD/Documentos/Metodolog%C3%ADa_calculo_inventario_GEI_2020.pdf.
Richa, K., Babbitt, C.W., Nenadic, N.G., Gaustad, G., 2017. Environmental trade-offs across cascading lithium-ion battery life cycles. Int. J. Life Cycle Assess. 22 (1), 66–81. http://dx.doi.org/10.1007/s11367-015-0942-3.
Saez-De-Ibarra, A., Martinez-Laserna, E., Stroe, D.I., Swierczynski, M., Rodriguez, P., 2016. Sizing study of second life li-ion batteries for enhancing renewable energy grid integration. IEEE Trans. Ind. Appl. 52 (6), 4999–5007. http://dx.doi.org/10.1109/TIA.2016.2593425.
Saini, H.S., Srinivas, T., Vinod Kumar, D.M., Chandragupta Mauryan, K.S., 2020. In: Saini, H.S., Srinivas, T., Vinod Kumar, D.M., Chandragupta Mauryan, K.S. (Eds.), Innovations in Electrical and Electronics Engineering Proceedings of the 4th ICIEEE 2019. In: Lecture Notes in Electrical Engineering, vol. 626, Springer, Singapore.
Simpson, J.G., Hanrahan, G., Loth, E., Koenig, G.M., Sadoway, D.R., 2021. Liquid metal battery storage in an offshore wind turbine: Concept and economic analysis. Renew. Sustain. Energy Rev. 149 (April 2020), 111387. http://dx.doi.org/10.1016/j.rser.2021.111387.
Sun, S.I., Chipperfield, A.J., Kiaee, M., Wills, R.G., 2018. Effects of market dynamics on the time-evolving price of second-life electric vehicle batteries. J. Energy Storage 19 (May), 41–51. http://dx.doi.org/10.1016/j.est.2018.06.012.
Sundararagavan, S., Baker, E., 2012. Evaluating energy storage technologies for wind power integration. Sol. Energy 86 (9), 2707–2717. http://dx.doi.org/10.1016/j.solener.2012.06.013.
Tam Thanh, N., Maik, N., Cong Nam, T., Andreas, J., 2018. Techno-economic evaluation of energy storage systems built from EV batteries - Prospective revenues in different stationary applications. E3S Web Conf. 64, http://dx.doi.org/10.1051/e3sconf/20186403003.
Tang, Y., Zhang, Q., Li, H., Li, Y., Liu, B., 2019. Economic analysis on repurposed EV batteries in a distributed PV system under sharing business models. Energy Procedia 158, 4304–4310. http://dx.doi.org/10.1016/j.egypro.2019.01.793.
United Nations, 2016. The 2030 Agenda for Sustainable Development. Technical Report, United Nations, pp. 12–14. http://dx.doi.org/10.1201/b20466-7, URL: https://sustainabledevelopment.un.org/content/documents/21252030AgendaforSustainableDevelopmentweb.pdf.
Vatsala, Khan, R.H., Varshney, Y., Ahmad, A., Alam, M.S., Chaban, R.C., 2018. ISGW 2017: Compendium of Technical Papers, Vol. 487. Springer Singapor, pp. 151–164. http://dx.doi.org/10.1007/978-981-10-8249-8, URL: http://link.springer.com/10.1007/978-981-10-8249-8.
Wilson, J., 2021. Electric car battery life. Buyacar.co.uk URL: https://www.buyacar.co.uk/cars/economical-cars/electric-cars/1615/electric-car-battery-life.
Xiong, R., Zhang, Y., Wang, J., He, H., Peng, S., Pecht, M., 2019. Lithium-ion battery health prognosis based on a real battery management system used in electric vehicles. IEEE Trans. Veh. Technol. 68 (5), 4110–4121. http://dx.doi.org/10.1109/TVT.2018.2864688.
Zhan, S., Hou, P., Enevoldsen, P., Yang, G., Zhu, J., Eichman, J., Jacobson, M.Z., 2020. 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. 117 (October 2019), 105631. http://dx.doi.org/10.1016/j.ijepes.2019.105631.
Zhang, Z., Mei, D., Jiang, H., Liu, G., He, H., Chen, Y., 2018. Mode for reducing wind curtailment based on battery transportation. J. Mod. Power Syst. Clean Energy 6 (6), 1158–1171. http://dx.doi.org/10.1007/s40565-018-0421-5.