Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases

The corrections made in this section will be reviewed and approved by a journal production editor.

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Handling editor: Cecilia Maria Villas Bôas de Almeida

Abstract

Electric vehicles (EVs) are considered a viable alternative to internal combustion engine vehicles (ICEVs) and as a result of recent advances in battery technologies, sales are increasing year by year. However, recycling these batteries at the end of their useful life in the car can be a problem because they contain materials that can harm human health and the environment. Thus, car manufacturers consider that when those batteries have finished their first life in an EV, they still contain enough energy and capacity to be used in a stationary energy storage systems (SESSs), significantly contributing towards an increased sustainable transport sector in the future.This study focuses the analysis on the viability of a SESS installation, considering battery ageing from an economic perspective in two different real scenarios in Spain. This study simulates the electricity bill cost with and without SESS and calculates the annual savings accordingly. Following, the return on investment (ROI) of installing a SESS is calculated. Afterwards the lifetime of the batteries is calculated in order to compare it with the ROI and to decide if the installation of a SESS is advisable from an economic point of view.Major results indicate that any feasibility study of installing a SESS must be studied from an economic and battery ageing point of view.

Keywords: Electric vehicle; Battery second life; Stationary energy storage system; Battery ageing research; Economic analysis

Abbreviations

DOD	Depth of Discharge
SESS	Stationary Energy Storage System
EV	Electric Vehicle
ICEV	Internal Combustion Engines Vehicle
Li-ion	Lithium-ion
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaics
ROI	Return of Investment
SME	Small and Medium Enterprises
SOC	State of Charge
SOH	State of Health
UPS	Uninterruptible Power Supply

1 Introduction

The global electric vehicle (EV) market is increasing annually due to governments pressure on car manufacturers to produce less polluting cars (European Parliament, 2011). Even though EVs are more environment and climate-friendly than internal combustion engines vehicles (ICEVs) (Wilberforce et al., 2017), the disposal of EV batteries at the end of their automotive lifecycle has emerged as a serious environmental concern. Lithium-ion (Li-ion) batteries used in EVs contain metals, rare earth elements and toxic materials that adversely affect the environment and pose risk to human health (Kang et al., 2013). Therefore, scrap EV batteries should be recycled at dedicated facilities to recover valuable materials efficiently and safely. The two main recycling processes are pyrometallurgy or smelting and hydrometallurgy, being chemical separation processes that are often used together or in various combinations to recover most of the materials within the battery (Moradi and Botte, 2016). There are other processes, such as the mechanical approach to recover metals by extracting the electrolyte and breaking the cell apart (Ordoñez et al., 2016) or the leaching and precipitation used to focus on Lithium and Cobalt (Porvali et al., 2019), that might be used as recycling processes to maximize the recovery of elements. However, due to the still low quantity of EV batteries sent to recycle and their existing different types (different shape, size, chemistries, etc...) makes automation and specialization difficult. This causes the recycling processes to treat batteries like a general waste, focusing on recovery only the critical raw material. Consequently, these recycling approaches do not provide enough economic profit. For instance, 1 Kg of CO_2 is saved per each kilogram of recycled battery, but recycling Li-ion batteries is five times higher than extracting virgin material (Jonathan Eckart, 2019). At the moment, only 5% of Li-ion batteries are recycled across Europe (Beall, 2019).

On the other hand, EV manufacturers usually recommend EV battery replacements when their State of Health (SOH) has decreased to around 70–80% or roughly after 8 years or 160,000 km (Viswanathan and Kintner-Meyer, 2011). Otherwise a proper performance cannot be guaranteed in the car in terms of distance travelled per charge, which in most cases is a consequence of the battery's capacity loss (Faria et al., 2014). However, even after such capacity loss, these batteries still have enough energy to be used for other less demanding second life purposes, such as in stationary energy storage systems (SESSs) and thus they can be reused while delaying the final recycling phase by up to 20 years, leaving space for recycling to present positive revenues (Saez-de-Ibarra et al., 2015). Moreover, the SESS's requirements are much lower than the ones of EVs, which corroborates that the loss of power and capacity of reused batteries is not a major problem for most stationary energy applications (Riegel, 2018).

EV manufacturers want to take advantage of the possibility of giving these batteries a second life in so called Battery Second Use (B2U) applications to open up new business cases, which could allow for a reduction in the final EV selling price (Jiao and Evans, 2016). The battery cost represents around 30%–40% of the EV final price (Canals Casals et al., 2015). Therefore, the reuse of these batteries could be a key factor for EVs to definitely overpass conventional ICEVs and to accelerate the transition of the transport sector into a sustainable future (Lih et al., 2012).

However, between the first and second life of batteries there is a regulatory gap to cover. Regulations around Europe state that the company that introduces batteries, either alone or included in a product such as in the case of EVs, is also responsible of organizing the final collection and correct management for recycling. However, the introduction of the battery re-use puts a new actor in between. The discussion over the final responsibility of these batteries' end-of-life management is something that all involved actors want to close to have a clear picture of the legal framework. In the case of Spain, some 2nd life companies are using the possibility that offers the directive 2008/98 for electronic waste management. This directive has a chapter on "preparation for re-use" (previous to recycle) that consist on a check, cleaning and/or repairing to re-use the whole element or its components without any previous transformation, so they consider the battery as an electronic equipment, although knowing that this might be not entirely true. In addition, it should be taken into account that not all EV batteries will fit second life purposes. Depending on the SOH, batteries could be re-used back into vehicles as replacements (when SOH is high enough), to second life, or directly to dismantling and recycling (when SOH is really low). Moreover, in cases of massive crash of an EV, it would certainly be very risky to re-use its battery and it could have sense to send it to recycle it directly.

Even having a lack of clarity from a legal perspective, battery re-use seems to be attractive and all actors involved are beginning to work on it independently. Table 1 shows how EV manufacturers launched demonstration projects for reusing these batteries as SESS, usually by the hand of electricity companies. This means that these new business opportunities are not only interesting for EV manufacturers, other actors such as electricity providers or B2U energy storage system and service providers are going to play an important role at the entrance of the SESS in the electric sector because the emergence of cross-sectoral multi-stakeholder innovative business relationships has been confirmed, which ultimately contributes to the business case for sustainability within the rapidly developing the EV sector (Reinhardt et al., 2019).

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Table 1

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Examples of projects using second life batteries carried out by car manufacturers (Rallo, 2018).

EV MANUFACTURER	ELECTRICITY COMPANY	PILOT PROJECT DESCRIPTION

SEAT	Endesa	4 reused PHEV batteries installed in a portable marine container offering energy services with an energy capacity of 40 kWh.
GENERAL MOTORS	ABB	5 Chevrolet Volt Li-Ion batteries, 74 kW solar array and two 2 kW wind turbines to power a GM office building
BMW	Vattenfall/Bosch	Pilot system using 100 Li-ion batteries from BMW ActiveE and i3 models
Groupe PSA	Electricite De France/Forsee Power	Pilot study: use of batteries removed from Peugeot iON, Citroen C-Zero and Mitsubishi i-MiEV
DAIMLER	GETEC/The Mobility House Remondis/EnBw	Energy storage system with a total capacity of 13 MWh using used batteries from Daimler electric vehicles
NISSAN	Sumitomo	System (600 kWh/400 kWh): 16 Nissan Leaf LIBs regulate the power of a solar plant in Osaka, Japan
RENAULT	Connected Energy	Recharging system for electric vehicles with 50 kW of power and 50 KWh of storage using reused batteries.
DAIMLER	Enercity	Grid-connected storage system with 5 MW of power and 17.4 MWh of storage using reused batteries
NISSAN	Eaton Power	Uses 280 recovered Nissan Leaf batteries that, in their second life, will provide power to the Ajax stadium, the Amsterdam Arena, with a storage capacity of 4 MW.

The aforementioned projects demonstrated the technical feasibility of using EV batteries as a SESS in many different applications and locations. For instance, the SUNBATT project led by SEAT was one of the first projects that demonstrated good performance of the EV batteries working as a SESS in Spain. The SUNBATT container (Fig. 1 left) is connected to an 8 kW solar carport, 3 EV chargers, 1 Fast EV charger and the grid, which is able to offer 90 kW peak power. All these elements interact with the energy storage system though an energy management system offering a variety of possible applications and it allows testing the different real case stationary applications before releasing the product into the market (Canals Casals et al., 2019a). In 2019, AUDI has put into operation the largest multi-use storage in Germany (Fig. 1 right). The storage unit has a capacity of 1.9 MWh and uses used Li-ion batteries from vehicles to test various scenarios having different interactions between electric cars and the power grid (AudiMediaInfo, 2019). Another illustrative success case has been found with BMW developing a storage facility that consists of 2600 battery modules from over 100 electric vehicles. It has a power rating of 2 MW and a storage capacity of 2800 kWh (BMW, 2019).

alt-text: Fig. 1

Fig. 1

Left: SUNBATT container located at technical centre of SEAT (Martorell – Barcelona). Right: Audi Battery Storage Unit on Berlin EUREF Campus.

Energy arbitrage, peak shaving, load following, black start, power oscillation damping, wind power gradient reduction, wind power forecast accuracy improvement, voltage support, primary reserve, secondary reserve and tertiary reserve are the main uses that a SESS can perform integrated to the electrical network. Grid operators can take advantage of SESS for all these uses, but only the first two can be implemented at the end-customer level and always downstream of the meter (Komarnicki, 2016). Focusing the attention on what individuals can do to implement energy storage, this study analyses the uses of energy arbitrage and peak shaving. The purpose of energy arbitrage is to store low-price energy during periods of low demand and subsequently using it during high-price periods. On the other hand, although the purpose of peak shaving could seem similar, its main objective is to trim the energy consumption peaks when those exceed the contracted power that leads to additional cost overruns that would be charged by the grid operator (Lott and Kim, 2014).

Since it has been demonstrated that at technical level there are solutions to integrate these batteries into the grid, it is time to dive into the economic side. Second life batteries have shown that together with the integration of Photovoltaics (PV) renewable energy is possible to reduce the cost of the electricity bill for the end user in addition and also to the investment cost that is lower due to the narrow price of the batteries (Saez-de-Ibarra et al., 2015). These batteries can be also integrated in an off-grid photovoltaic EV charge system achieving similar performance than using new li-ion batteries, but at half cost (Tong et al., 2013). Furthermore, a second life battery pack, properly sized, is able to deliver the equivalent performance of a new battery pack but at a larger volume and lower cost (Tong and Klein, 2014). Another important thing these batteries have shown, is that, apart from being a cost-effective alternative either to the new Li-ion or Lead-Acid batteries, they have a lower environmental impact (Ambrose et al., 2014).

On the other hand, some authors indicate that the SESSs, nowadays, are not financially viable under current market conditions without additional subsidies and payments from the grid controllers (Bassett et al., 2018). Furthermore, the results suggest that SESSs do not generate sufficient incentives with the energy arbitrage strategy (Scott B Peterson et al., 2010). A new variable was introduced to determine if the investment on SESS is economically feasible such as the battery acquisition price, being the breakeven in their studies 107€/kWh and 73€/kWh (Madlener and Kirmas, 2017). Even though the investment costs of some SESS technologies have decreased over the last few years, few business models seem to be attractive for investors (Lombardi and Schwabe, 2017).

Although there are many articles studying the economical profit of using a SESS, only very few studies have evaluated the economic benefit of these applications taking into account the real ageing of those batteries. For example, these 2nd life batteries are used to improve the power quality of commercial and industrial end users can achieve a payback periods from 7 years to 10 years (Neubauer et al., 2012). Conversely, although the SESSs have been considered the perfect system for reducing the energy mismatch of PV supply and energy demand, when the battery degradation is considered, the SESS owner is subject to a significant financial loss. In addition, even without taking into account the aging of the battery; the integration of a SESS in a photovoltaic system is not profitable. (Uddin et al., 2017).

Furthermore, most studies finish their ageing tests when the batteries have achieved the 80% SOH, just at the point that is considered that the second life should start (Scott B. Peterson et al., 2010). Additionally, most of these studies use inaccurate aging models. In fact, many of them use basic models based on the expected number of cycles, the accumulated Ah throughput or on expected lifetime adjusted by temperature or, in best cases, with more than one factor (Devie and Dubarry, 2016). Moreover, up to now, no article has studied the economic viability of the installation of a SESS comparing energy arbitrage and peak shaving strategies using data of real applications and considering batteries ageing until those have reached the end of their second life.

For this reason, the objective of this study is to fill a gap in knowledge by evaluating the profitability of second life cases for degraded EV batteries, followed by an analysis on how long these batteries will in fact perform in optimal conditions. This will be done by an ageing evaluation of the batteries and the economic study on using them as a SESS integrated in two real scenarios using real data. The comparison of the two results will determine whether the installation of a SESS is cost-effective. Consequently, it is necessary to determine the costs of investment, savings per year, operating costs and the estimated battery life for each case study.

2 Methodology

This section defines how the study analyses the economic impact that has the installation of a SESS using batteries in their second life in real scenarios taking into account the battery ageing. In 2018, Small and Medium Enterprises (SMEs) generated 65.9% of total employment in Spain, similarly to that of the European Union average (Ortega, 2019). Consequently, this study focuses the analysis in SMEs considering a company of the industrial sector and a company of the hotel sector. Next, the details of the whole calculation process are presented, indicating how it determines the feasibility of installing a SESS from the point of view of the battery ageing and the economic return.

2.1 Process of calculating the feasibility of installing an SESS

The calculation process is divided, as shown in Fig. 7, in twelve points that describe the calculation process. These points are:

1. Select the case study and run the economic model

The first step in the process is to select the case study to analyse. In this article, two cases will be studied as shown in Table 2.

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Table 2

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Case studies.

	Profile	Location	Type of access tariff	Contracted power [kW]
Case study 1	Furniture factory	La Sénia (Tarragona)	3.0 A	80 kW
Case Study 2	Hotel	Santa Cruz de Tenerife (Canary Islands)	6.1 A	490 KW

The first case corresponds to a furniture factory located in “La Sénia” (Tarragona) with an electrical contract at tariff 3.0 A and with a maximum contracted power of 80 kW. Fig. 2 shows the power yearly demand for the case study 1. It can be observed that there are many spaces of time where the electrical demand is almost zero. The three bigger ones correspond to the Easter, summer and Christmas holidays respectively. All the other low consumption valleys, the smaller, correspond to weekends, since the company only works from Monday to Friday. It can also be observed that the maximum power demand changes daily because of the variability of the plant production.

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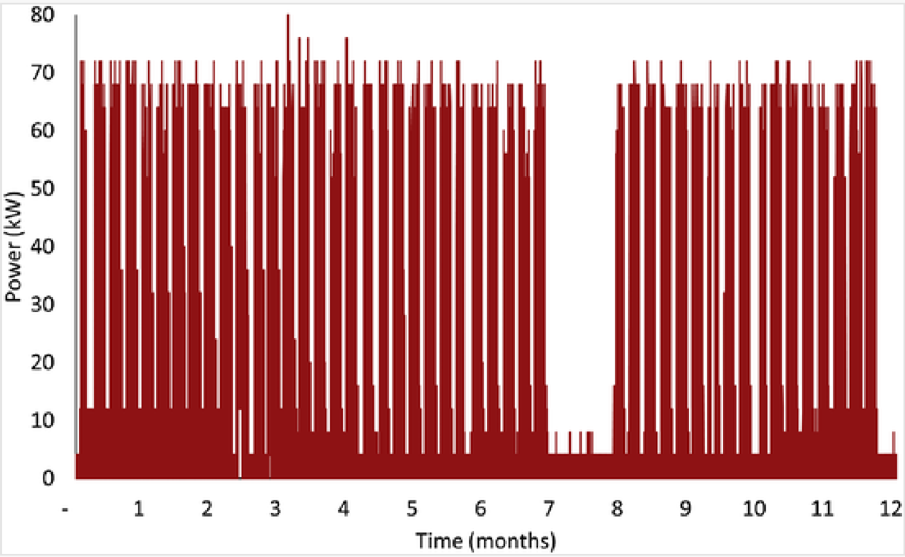
Fig. 2



Power yearly demand for the case study 1.

In contrast, the second case corresponds to a hotel located in Santa Cruz de Tenerife (Canary Islands) with an electrical contract at tariff 6.1 A and with a maximum contracted power of 490 kW. Fig. 3 shows the power yearly demand for the case study 2. In this case there are no times of null consumption because the hotel is open

24 h every day of the year. It is important to notice that electricity consumption varies throughout the year in the range of 100–600 kW showing a slight increase in winter.

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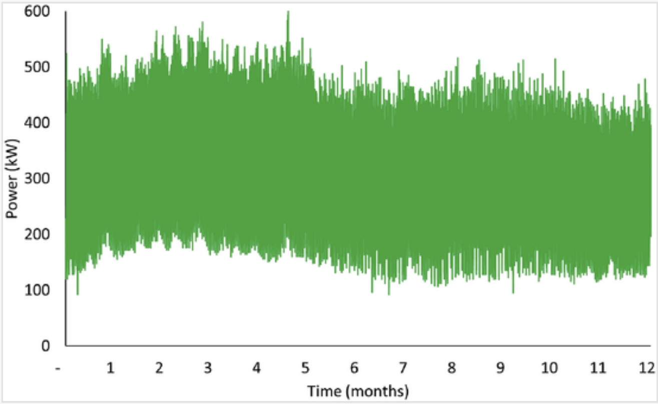
Fig. 3



Power yearly demand for the case study 2.

Seeing that the behaviour in both cases is very similar during work-days for scenario 1 (Fig. 2) and for the whole week in scenario 2 (Fig. 3), a randomly chosen day is taken as example (Fig. 4) of the daily electricity consumption for scenarios 1 and 2. See how there is an increase in the consumption from 7 to 16 h in the scenario 1, while the consumption in scenario 2 increases when the sun rises and decreases after 22 h in the night.

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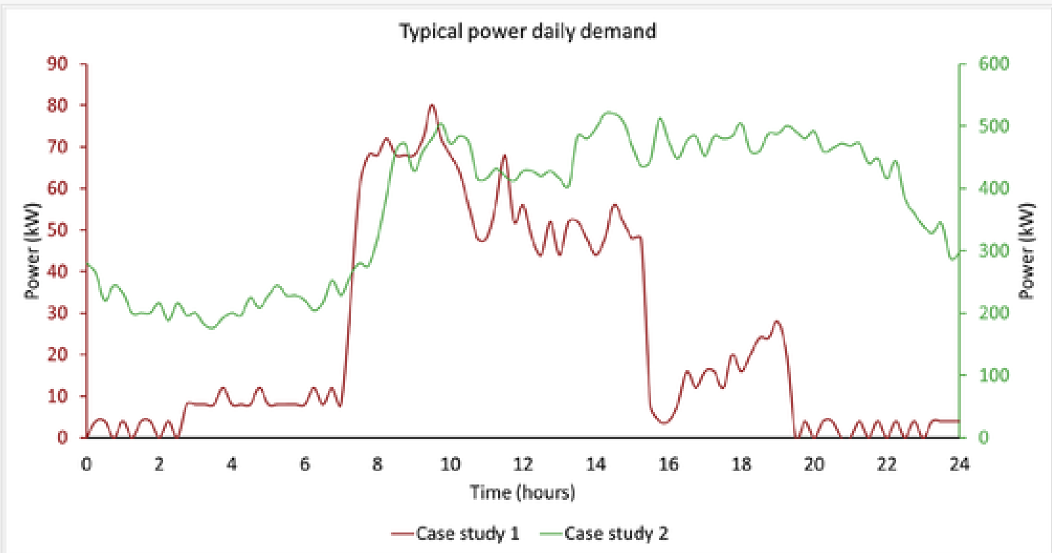
Fig. 4



Typical power daily demand for the case of study 1 & 2

Note that this study is based on the registers of a complete year. These registers have been obtained directly from the electric meter of each installation under study during the year 2018.

These power profiles of each scenario are introduced in the economic model developed in this work. The economic model, programmed using MATLAB, calculates the greatest economic savings in terms of electricity bill considering the installation of an SESS. This model calculates the size of the SESS to maximize the profit and, accordingly, calculates the SESS charging and discharging power. The application of this model in this process goes from point 1 to point 9.

2. Calculate the real electricity bill without SESS

This point calculates the economic cost of electricity consumption for each of the scenarios during the year under analysis according to the law of the Spanish electric sector (Ministerio de Industria, 2013) and the law RD1164/2001 where access tariffs to the electricity distribution networks are established (BOE - Boletín Oficial del Estado, 2001).

Table 3 shows the electricity prices (€/kWh) that have been used in the simulation for both case studies, each one with the corresponding access tariff. These prices correspond to the average prices during 2018 of the five electrical companies with the highest turnover in the same year. Each of the periods indicated in Table 3 correspond to the different schedules according to each electric tariff as determined by the electricity regulations.

Electricity price [€/kWh].

3. Calculate SESS power & capacity

	TARIFF 3.0A	*TARIFF 6.1A*
Period 1	*0.1112 € / kWh*	*0.101173 € / kWh*
Period 2	*0.090727 € / kWh*	*0.089755 € / kWh*
Period 3	*0.066407 € / kWh*	*0.079262 € / kWh*
Period 4		*0.07277 € / kWh*
Period 5		*0.069834 € / kWh*
Period 6		*0.060671 € / kWh*

In this section, the most important SESS parameters that fit the case study are calculated. This action is repeated until the parameters that contribute to a better use of the SESS and greater profits are found. It is important to dimension the SESS well in order to obtain the largest possible savings.

It should be noted that both, upper and lower SOC margins, have been left in the batteries for safety reasons. The upper limit is set at 95% and the lower limit at 10% of SOC. These limits mean that the available capacity in each battery is reduced, and thus a higher number of batteries is needed.

Additionally, the capacity in the economic model has been calculated considering that the SESS must be able to work until batteries reach the end of their second life. This means that the SESS capacity must be oversized considering the battery ageing.

Considering that the share of PHEV sales is higher than that of EV, and this is expected to be maintained according to (Sijabat, 2018) at least until 2023, this study will use these type of vehicles to use their batteries. Therefore, within approximately 8 years once these batteries have reached their end of life in the car, larger volumes of PHEV batteries will be available for use as SESS.

4. Estimate new electricity contract parameters and simulate electricity bill cost with SESS.

The installation of a SESS causes the modification of the parameters of electrical contracting to reduce its cost. In this section, the new parameters of the power term are calculated. Electricity bill cost is simulated using strategy 1 and 2 as explained in **point 2**.

- Strategy 1: ENERGY ARBITRAGE

The battery is charged during the cheapest period of the day. The battery is discharged during the most expensive period of the day. Loading/unloading is only carried out if possible.

- Strategy 2: PEAK SHAVING

The battery is charged during the cheapest period of the day. The battery is discharged when there is excess power demand of the contracted power.

The economic model always prioritizes the use of the energy available in the battery when the economic profit margin is higher. The battery charge and discharge decision are made based on two system variables: battery status and time varying electricity price. Therefore, the main objective of the model is to find a daily strategy between charging and discharging where profits are maximized (Pelzer, 2019). Consequently, the charging and discharging strategy is even more fundamental point for second life batteries to provide a beneficial business case (Gohla-Neudecker et al., 2015).

At this point, the power curve with which the SESS will work under the conditions set throughout the whole year of study is obtained.

5. Compare and calculate annual savings

This section compares the real cost of each scenario with the best of the simulated results and calculates the possible annual savings that the installation of a SESS would entail by the following equation.

$$Savings = Real\ cost - Simulated\ low\ cost = [€] \quad (1)$$

6. Calculate SESS configuration and electrical parameters

The SESS is built with the connection of several batteries in series and in parallel which will determine the voltage and total capacity of the SESS. Fig. 5 shows the rated, minimum and maximum voltage, the nominal capacity and the energy, at cell, module and full battery level of the batteries used in this study.

alt-text: Fig. 5

Fig. 5

	Cell	Module (12S1P)	Battery (96S1P)
Rated voltage (V)	3.67	44.04	352.32
Minimum voltage (V)	3.43	41.16	329.28
Maximum voltage (V)	4.17	50.04	400.32
Nominal capacity (Ah)	25	25	25
Nominal energy (Wh)	91.75	1101	8808
Energy at 80% SOH (Wh)	73.40	880.20	7046
Energy at 60% SOH (Wh)	55.05	660.60	5284

Battery of the Volkswagen Golf GTE 1st generation (Volkswagen, 2019).

According to the results of point 3, the SESS configuration taking into account the battery of the Golf GTE (Fig. 5) is calculated using equations (2) and (3). By means of the battery data sheet that is intended to be used and the cell data sheet, it is determined how many batteries must be connected in series and in parallel to obtain the capacity.

$$SESS_{voltage} = Cell_{voltage} * \ N^{o}\ batteries\ series\ = [V] \quad (2)$$

$$SESS_{capacity} = Cell_{capacity} * \ N^{o}\ batteries\ parallel = [Ah] \quad (3)$$

7. Calculate CELL current

At this point, the current that passes through each of the battery cells is calculated. First, using the power curve profile of the battery calculated in point 4, the SESS current is determined. Afterwards, as in the Golf GTE battery cells all are in series, the total SESS current is divided by the number of batteries in parallel in the SESS to get the current in each cell (Volkswagen, 2019).

$$SESS_{current}\ (i) = \frac{Battery_{power}}{SESS_{voltage}} = [A] \quad (4)$$

$$Cell_{current}\ (i) = \frac{SESS_{current}}{N^{o}\ batteries\ parallel} = [A] \quad (5)$$

8. Calculate SESS cost investment

At this point the total cost of purchasing a SESS is calculated by considering the battery 2nd life cost, the inverter cost, the material cost and the labour cost. Other elements such as operating and maintenance costs, replacement costs, end-of-life costs and financial costs are outside the scope of the study.

Estimating the purchase price of second life batteries is one of the most delicate points of this study, as it is a product not yet available in the market and there are many price variations in the literature consulted, the results can change considerably (Anseán et al., 2013) considered that the cost for these batteries should not exceed 100 €/kWh (Rallo et al., 2020). (Saw et al., 2016). Further on (Elkind, 2014), says that EV owners should expect between 20€/kWh and 100€/kWh for selling its used battery and (Neubauer et al., 2012) forecasted the cost of 2nd life batteries between 38€/kWh and 132€/kWh. Nonetheless, all authors coincide with the fact that the cost of the reused batteries should be lower than 50% of the new ones (Cready et al., 2003). Taking all of this into account, the price of the battery in this study is estimated at 50€/kWh when it reaches an 80% of SOH. Furthermore, Table 4 shows others considered costs in the study, such as the cost of the installation of power electronics and equipment (specific cost per power), costs of electric material and labour costs, according to (Díaz-González, 2018).

alt-text: Table 4

Table 4

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SESS investment costs per unit.

Specific cost per storage	50 €/kWh
Specific cost per power	80 €/kW
Specific cost of material	30 €/kW
Specific cost per labour	30 €/kW

Using equations (6)–(9) the cost of each component of the SESS cost are calculated for later solving equation (10) find the total cost.

$$Battery\ 2nd\ life\ cost\ (B2LC) = SESS\ Capacity\ [kWh] * Specific\ cost\ per\ storage\ [€/kWh] = [€] \quad (6)$$

$$Inverter\ cost\ (IC) = SESS\ Power\ [kW] * Specific\ cost\ per\ power\ [€/kW] = [€] \quad (7)$$

$$Material\ cost\ (MC) = SESS\ Power\ [kW] * Specific\ cost\ of\ material\ [€/kW] = [€] \quad (8)$$

$$Labour\ cost\ (LC) = SESS\ Power\ [kW] * Specific\ cost\ per\ labour\ [€/kW] = [€] \quad (9)$$

$$SESS\ Cost\ Investment = B2LC + IC + MC + LC = [€] \quad (10)$$

9. Calculate Return of Investment (ROI)

The last step of the economic model is to calculate the return on investment considering the necessary investment and the savings that the installation of the SESS produces annually in each of the scenarios.

$$ROI = \frac{SESS\ Cost\ Investment}{Savings} = [Years] \quad (11)$$

10. Run Cell ageing model & calculate cell ageing

Once all the economic parameters have been calculated, at this point, the aging model is applied to determine the lifetime of the SESS. The battery ageing model was developed in a previous work (Canals Casals et al., 2017) using MATLAB and SIMULINK. As Fig. 6 shows, the model takes into account temperature, State of Charge (SOC) and time to estimate the calendar ageing. In the cycling ageing, a part of the three previous variables, Depth of Discharge (DOD) and C-rate are also considered. The model outputs are the internal resistance increase, the capacity loss and the SOH as well as DOD and the cell voltage.

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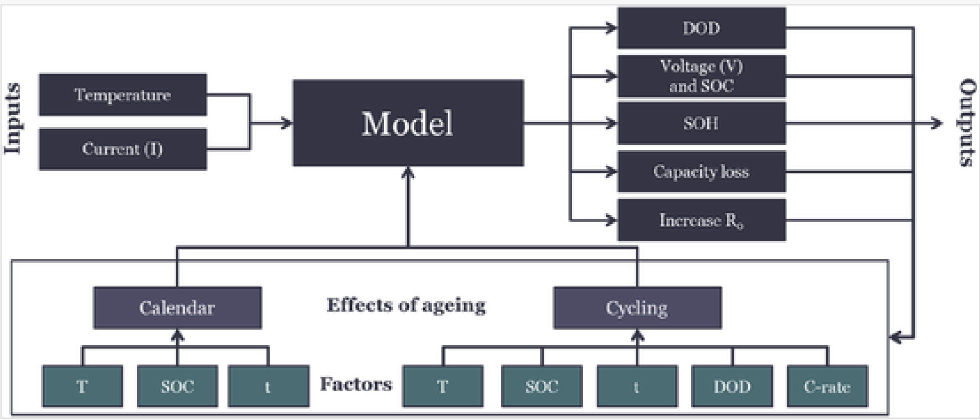
Fig. 6



Ageing battery model made using MATLAB – Simulink (Canals Casals et al., 2017).

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Fig. 7

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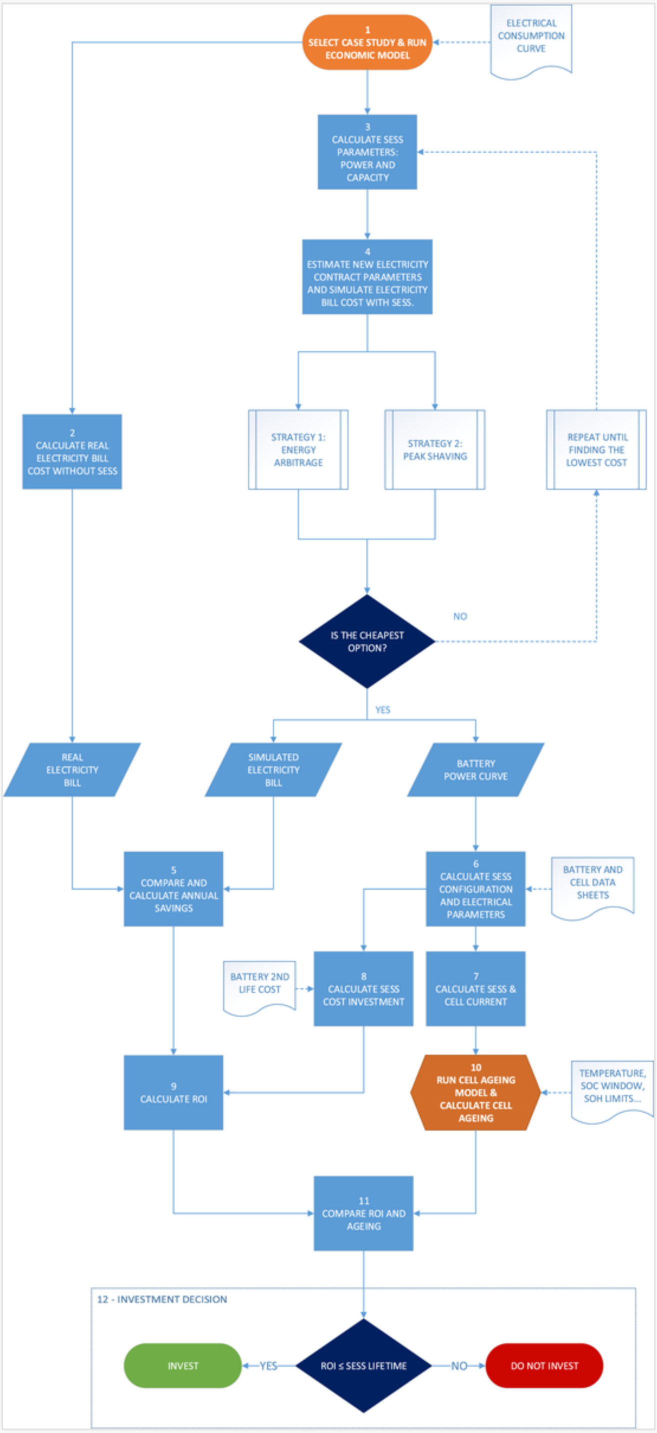

Calculation process.

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The working conditions of the cell-ageing model are set as Table 5 shows. First, the SOC limits follow the battery working parameters established by VW (Volkswagen, 2019). Then, temperature has been set at 23 °C (room temperature) due to the Association of the German Automotive Industry recommends in the test specification for Li-ion battery systems for hybrid electric vehicles that this is the best temperature to slow down the ageing phenomena of the batteries (Verband der Automobilindustrie, 2007) and when lesser lithium depletion occurs (Jaguemont et al., 2016). In the studied scenarios the temperature can always be kept relatively constant since the SESS remains in a controlled air-conditioned room. Finally, it has been considered the end of the lifetime of the batteries in their second life in 60% SOH because it cannot be assured that there will not be a dramatic change in the ageing behaviour from this point onwards (Lluc Canals Casals, 2016) (Universiteit et al., 2019).

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Table 5

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Cell ageing model-working parameters.

11. Compare ROI and ageing

SOC	Lower security limit	10%
	Upper security limit	95%
SOH	Initial point	80%
	Final point	60%
Temperature		23 °C

Straightaway, the cell current calculated in the point 7 is introduced as the main input. The ageing model calculates the cell lifetime under the conditions described.

This section compares the results obtained by both the economic model in terms of the ROI of the investment and the battery-aging model in terms of the lifetime of the SESS.

12. Investment decision

This last step decides if the investment in the installation of a SESS is economically viable. If ROI is bigger than the SESS lifetime, the investment is feasible. In contrast, if ROI is smaller or equal than the SESS lifetime, the investment is not feasible. Fig. 7 shows the calculation process.

3 Results and discussion

This section presents the results of all the points in the process of calculating the feasibility of installing an SESS. This section follows the same order of the previous sections, presenting simultaneously the results of both case studies and comparing them step by step.

The first result obtained, as shown in Table 6, is the cost of the electricity bill in each scenario for one year. In the real case, the contracted power in the scenario 1 is 80 kW with a cost of 24.896,84 € during the year 2018, in contrast, for the same period, the contracted power in the scenario 2 is 490 kW with a cost of 328.968,84 €.

alt-text: Table 6

Table 6

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Electricity bill cost without SESS.

Without storage	Case study 1	Case study 2
Contracted power [kW]	80 kW	490 kW
Cost (€)	24,896 €	328,968 €

The following step is to calculate the main SESS characteristics. The main objective is to find the capacity and power that best suit each case. As Table 7 shows, SESS capacity in scenario 1 is 200 kWh and its power is 40 kW. In the scenario 2, the capacity is 5000 kWh and the power is 100 kW. These values were calculated by the economic model with the aim of achieving the greatest possible savings in each case.

alt-text: Table 7

Table 7

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SESS characteristics by case of study.

	Case study 1	Case study 2
Capacity [kWh]	200	5000
Power [kW]	40	100

Once the main parameters of each SESS have been calculated for each scenario, Table 8 shows the simulation results of the electricity bill taking into account the two selected strategies (energy arbitrage & peak shaving) together with the contracted power that entail the greatest savings. Marked in green the results of each scenario with a lower cost.

alt-text: Table 8

Table 8

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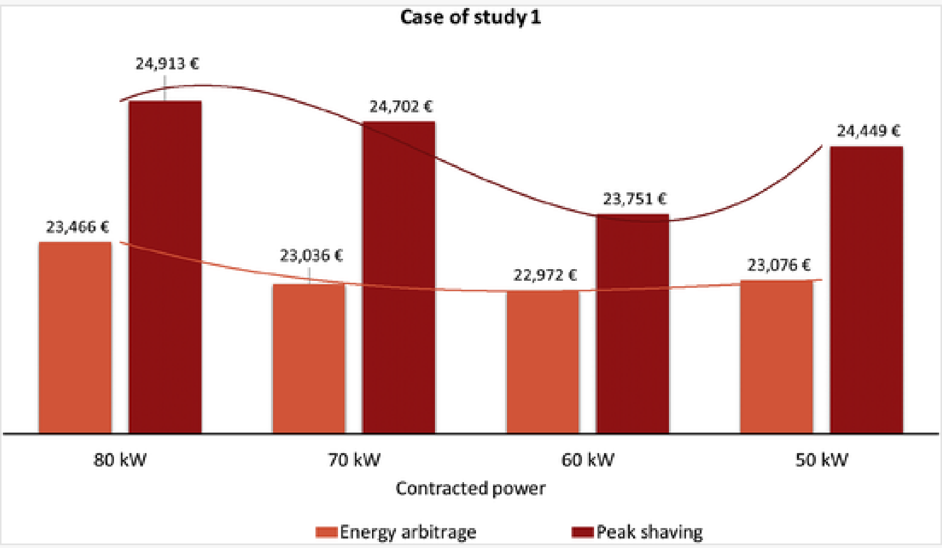
Simulated electricity bill using the two strategies for the cases of study.

	Contracted power	Energy arbitrage	Peak shaving
Case study 1	80 kW	23,465 €	24,912 €
	70 kW	23,035 €	24,702 €
	60 kW	**22,972 €**	23,751 €
	50 kW	23,075 €	24,449 €
Case study 2	490 kW	310,414 €	325,919 €
	450 kW	307,471 €	319,888 €
	400 kW	**306,603 €**	313,514 €
	350 kW	309,009 €	315,420 €

Fig. 8 and Fig. 9 compare graphically both strategies in each case study and show which are the tipping points where trends change, resulting in lower cost. It is interesting to note that in both study cases, the greatest savings were found following the energy arbitrage strategy. This occurs since the peak shaving has the only mission of cutting the power peaks when they exceed the contracted power. On the other hand, energy arbitrage, as explained above, aims to charge the batteries at times when the energy is cheaper, to use it when it is more expensive. However, what happens because of this strategy, is that the power peaks in the most expensive periods are also reduced since the electrical consumptions have moved towards the cheapest periods. Therefore, the energy arbitrage strategy indirectly could also be said is doing the peak shaving strategy for the case of analysis.

alt-text: Fig. 8

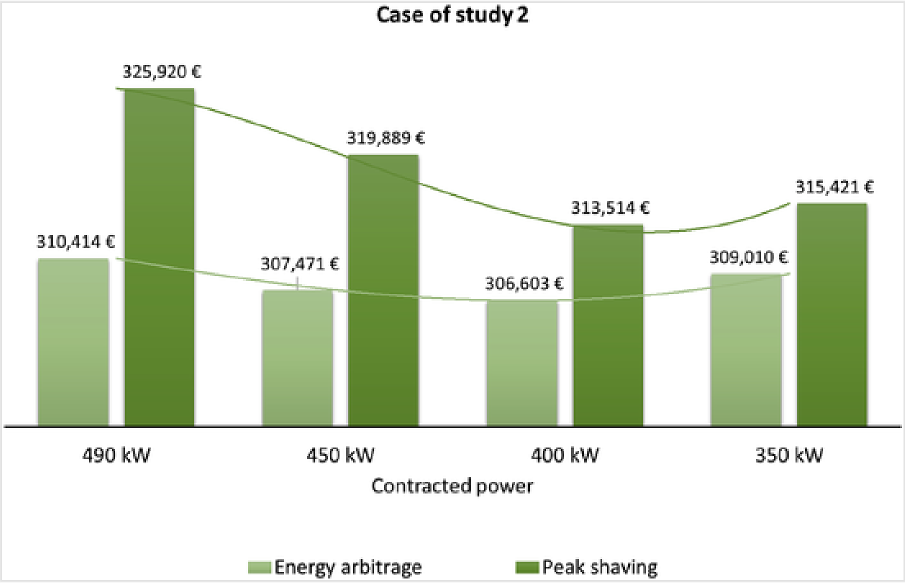
Fig. 8



Comparison of the simulated cost according to the strategy used in case study 1.

alt-text: Fig. 9

Fig. 9



Comparison of the simulated cost according to the strategy used in case study 2.

The next step is to calculate the configuration and parameters of the SESS in each case of study taking into account the battery parameters, as shown in Fig. 5, and the SESS requirements in terms of capacity and power calculated before as presented in Table 7, 9 shows the final configuration of the SESS for each case of study. The calculations have been made using equations (2) and (3) of the calculation process. In both cases, the capacity of the SESS has been calculated on the premise that the SESS must be able to offer the capacity determined by the economic model until the end of its useful life. Safety margins have also been considered. Consequently, 46 and 1116 batteries are needed to reach the SESS requirements in the case study 1 and 2 respectively. Only two strings in series are needed in each case to reach the first possible voltage value greater than 400 V due to this is the voltage value of the electrical network in Spain.

alt-text: Table 9

Table 9

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SESS configuration and electrical parameters by case of study.

SESS configuration	Case study 1	Case study 2
Number of batteries strings in series	2	2
Number of batteries in parallel	23	558
SESS voltage (V)	704.64	704.64
SESS capacity (Ah)	1125	13,950
SESS energy content (kWh) (new)	405.17	9829.73

SESS energy content (kWh) (2nd life – 80% SOH)	324.13	7863.78
SESS energy content (kWh) (2nd life – 60% SOH)	243.10	5897.84
SESS useful energy (kWh) with SOC working limits 15%	206.64	5013.16

Using equation (1), the savings that the installation of the SESS produces each year are calculated. The total cost of the investment is calculated using equation (10). Finally, one of the two most important values, ROI, can now be calculated. Equation (11) allows us to evaluate the return of investment for each case study. For the case of study 1, as it can be seen in Table 10, the ROI is 8.42 years, while for the second, it is 17.58 years.

alt-text: Table 10

Table 10

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

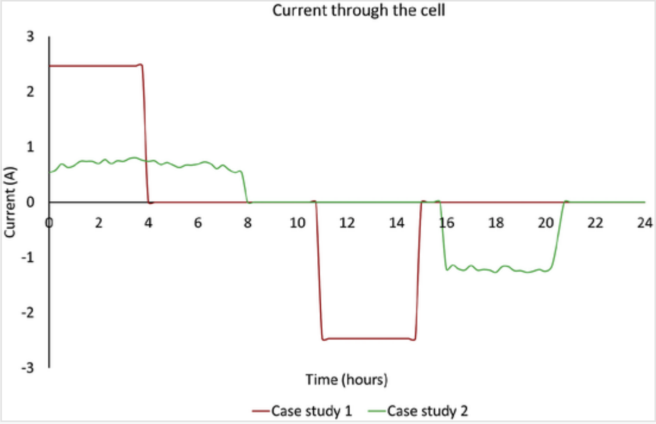
Savings, investment & ROI by case of study.

	Savings/year	SESS cost investment	ROI
Case study 1	1924 €/year	21,806.50	11.33 years
Case study 2	22,365 €/year	407,189.00	18.21 years

Once the economic model has calculated all the necessary parameters, the study proceeds to calculate the aging of the SESS to determine if the investment is profitable. Using equations (4) and (5) the cell current for each case is calculated as Fig. 10 shows. It can be clearly observed, in the two cases, that the battery absorbs energy from the grid during the early morning, when the price of energy is cheaper, to use it later in the moments where it is more expensive. Fig. 10 also shows that the C-rate either during the charge and discharge in both cases is lower than 0.12C (or C/8). These low current intensities mean that the temperature increase caused by the joule effect on these batteries can be considered as negligible.

alt-text: Fig. 10

Fig. 10

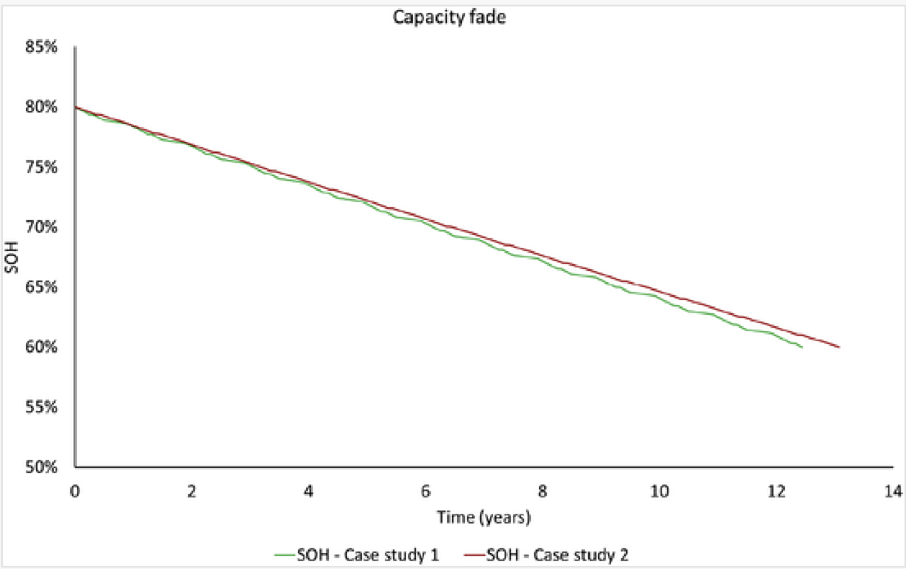


Cell current on a typical day. Case study 1 & case study 2.

Finally, the current profile that will pass through each cell will be introduced in the ageing model. Fig. 11 shows the capacity fade of each cell depending on the current above calculated. The simulation in both cases starts at 80% of SOH and ends at 60% getting 12.44 and 13.07 years of useful life in each case. It has been shown that the ageing of the SESS is very similar since in both cases the current that passes through the cells is less than 3 A, which means a C-rate of 0.12 when these batteries are used to working in currents up to 10C (Lam, 2011). Another interesting point to emphasize is that the aging of the batteries in both cases is practically lineal. This is justified because the stationary applications are assumed to have a less demanding cycling pattern and does not include degrading factors such as regenerative braking (Ahmadi et al., 2014).

alt-text: Fig. 11

Fig. 11



Cell capacity fade for case study 1 & case study 2.

With all the calculations and simulations performed, it is time to determine the economic viability of the SESS installation. As it can be observed in Table 11, in case of study 1, the ROI is smaller than the cell ageing, in fact 10% less, which means that for a little bit more than one year the SESS in this case will be generating economic benefits. On the other hand, the results in the case study 2 are quite the opposite, with the ROI 40% bigger than the cell ageing making the investment not economically profitable in any case.

alt-text: Table 11

Table 11

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ROI and Cell ageing comparison by case of study.

	ROI	Cell ageing	Investment
Case study 1	11.33 years	12.5 years	YES
Case study 2	18.21 years	13 years	NO

In case study 2, the capacity of the SESS is 25 times larger than in case study 1, and consequently, the investment as well. This is clearly the reason why the investment is in no way advisable. Although battery prices have dropped a lot in recent years, this is not enough to make the SESS installation attractive (Lombardi and Schwabe, 2017). Furthermore, in case study 1, although the ROI is smaller than the battery life, being such a small difference between them, the investment would also be discouraged. Seeing that, the importance of finding the (economically) optimal size for the different applications regarding battery capacity in order to maximize the return on each investment in each case is justified (Lombardi and Schwabe, 2017).

Although in the cases analysed it is shown that the economic viability of the SESS installation behind the meter with the actual battery prices seems not attractive for investors, other studies have demonstrated that the SESS could play a relevant role in the economic results working in secondary electricity markets where benefits could increase significantly (Canals Casals et al., 2019b).

Note that the re-use of EV batteries clearly offers an opportunity to enhance the circular economy way of thinking. If results are not dramatic (neither optimistic) when batteries are not even thought for re-use (which is the actual case), they could certainly improve when eco-design comes into play. Moreover, not everything should end-up in economics. From an environmental perspective, it is said that the battery re-use decreases the impact of the battery per kWh exchanged through lifespan enlargement and it avoids the manufacture of new batteries for this same purpose.

4 Conclusions

This study evaluates whether it is economically viable to install a SESS in two real cases of study in Spain using second life batteries that were previously used in a first life in the automotive sector.

This study combines the knowledge of the electricity market and strategies for reducing the price of the electricity bill using a SESS with the knowledge on battery ageing. From this investigation, it can be concluded that an appropriate ageing model combined with an economical study is a mandatory requirement to determine the feasibility of installing a SESS. In all the analysed cases, the study shows that the ageing of battery plays a relevant role in the economic results, although the price of batteries is the most important factor in determining whether the installation of a SESS is economically viable. This work, after calculating all the costs of the electricity bill, also shows that the energy arbitrage strategy produces higher savings than peak shaving strategy as it also indirectly performs peak shaving.

It is also proved that the best economic return is obtained by over-dimensioning the SESS, which will require a lot of space to install the SESS and will increase the complexity of the installation.

Although the results obtained in this work, do not present great economic savings, it is necessary to wait until the volume effect in the next few years will cause a drop in the price of batteries, so that all projects using second life batteries start to be attractive to investors. In addition, this will lead to greater investment in battery development that will also increase its energy capacity. If these two factors improve, the cases in which it will be economically interesting to install a SESS will increase. On the other hand, 2nd life batteries could reduce the effective price of EVs.

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.

Acknowledgments

The authors gratefully acknowledge the project REFER (COMRDI15-1-0036), funded by ACCIO and the European Regional Development Fund (FEDER) under the RIS3CAT Energy Community. Furthermore, the authors also acknowledge the Spanish government (ReViBE project TEC2015-63899-C3-1-R (MINECO/FEDER). Further, this work was also supported by Generalitat de Catalunya, AGAUR scholarship 2016 DI 060.

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The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

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Highlights

- Battery second life can reduce final EV selling price.
- Second life EV batteries still have enough energy & capacity to be used as a SESS.
- The current price of battery second life does not guarantee economic viability of the SESS.
- Energy arbitrage is the most profitable strategy to be used in a SESS.
- The battery ageing determines the economic viability of any SESS.

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