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Integration of LFP-second life batteries as a storage in a smart microgrid

Integración de baterías LFP-segunda vida como almacenamiento en una microrred inteligente

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ABSTRACT: In recent years, there has been an increasing commitment to give batteries a second life, as they are being consumed for different uses and the recycling methods are not defined. This work aims to show how a storage system based on disused Lithium Iron Phosphate (LFP) batteries has been recovered and integrated into the CE.D.E.R-CIEMAT smart microgrid over a period of ten years during which the operation of the system has been affected. During the recovery process, the cells have been classified according to their voltage, and a series of charge-discharge processes have been carried out on them at different voltages to determine their state of health and capacity. Once characterised, the system was assembled and commissioned with the appropriate cells. In addition, for the storage system, a Supervisory Control And Data Acquisition (SCADA) has been developed in Home Assistant for its integration into the CE.D.E.R.'s microgrid management system. This allows the microgrid to be managed more efficiently, storing surplus energy from distributed generation sources and discharging the stored energy during peak consumption periods to reduce peaks, reduce discharges to the distribution grid and reduce the cost of electricity bills.

RESUMEN: Ante el aumento del consumo y producción de baterías para diferentes usos en los últimos años y la problemática actual en la definición de los métodos de reciclaje, se apuesta cada vez más por dar una segunda vida a las baterías. El propósito de este trabajo es mostrar cómo se ha realizado la recuperación e integración en la microrred inteligente del CE.D.E.R.-CIEMAT de un sistema de almacenamiento basado en baterías Litio Ferro-Fosfato (LFP) en desuso durante diez años en los que se ha visto afectada la operación del sistema. Durante el proceso de recuperación, se han clasificado las celdas en base a su tensión y se les ha realizado una serie de procesos de carga-descarga a diferentes tensiones para determinar el estado de salud y capacidad. Una vez caracterizadas, se ha procedido al montaje y puesta en marcha del sistema con las celdas adecuadas. Además, se ha desarrollado un Control Supervisor y Adquisición de Datos (SCADA) del sistema de almacenamiento en Home Assistant para su integración en el sistema de gestión de la microrred del CE.D.E.R.. Esto permite gestionar la microrred de forma más eficiente, almacenando los excedentes energéticos de las fuentes de generación distribuida y vertiendo la energía almacenada en periodos de máximo consumo con el objetivo de reducir los picos, reducir los vertidos a la red de distribución y disminuir el coste en la factura de la luz.

1. Introduction

In the last 30 years, society has faced many problems related to the development of energy systems, the exhaustion of sources all around the world, economic recessions, climate change and CO_2 emissions [1]. To make society capable of confronting these problems, experts around the world have been working on investigations and developing new alternatives related to renewable energy sources and innovative energy storage

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systems.

Thus, alternatives to conventional energy generation and storage methods have become one of the priorities of governments in most countries around the world. One of the essential aims of these alternatives is to break up the harmful effect of fossil fuels throughout their life, since they are produced until their final uses [2–4].

One of the most important developing fields is the automotive sector, in particular Electric Vehicles (EV). The main reason why this sector has increased its offer in different car brands and their sales is the reduction of fossil fuel consumption and gas emissions, both at the European and global levels. The International Energy Agency (IEA) estimates that there are currently around 16 million EVs in the world, showing an increase that triples the registered sales data concerning the year 2021 in the People's Republic of China, and 70% in Europe [5].

This huge increase in sales of hybrid, plug-in hybrid, or pure EVs poses a challenge in battery management, both in production, and, even more so, in the management of batteries when they no longer meet the minimum characteristics required for automotive use and need to be replaced. This situation raises the question: what will we do with such a large number of batteries in a few years? To answer this question, studies on the useful life of batteries in vehicles have been initiated. The great majority of these studies, some of them such as [6–8], agree that after a period of approximately eight years of continued vehicle use, it would be appropriate to replace the vehicle's battery system because it no longer provides the energy requirements necessary to supply the vehicle's needs.

With these results, we see that batteries have suffered degradation in their primary use energy capacities and are not suitable for operation in this field, but are they suitable for use in other applications, or do they need to be discarded and taken to a recycling point? Different authors, such as [9–13], agree that batteries still have suitable capacities for use in other types of applications with a categorisation that they call "second-life battery". The most prominent applications, which would be carried out with optimum performance, for this are area regulation and energy storage systems to support grid services, microgrids, or renewable energies (RES). All these systems are characterised by being stationary and needing smaller amounts of energy over longer periods of time than in their first life uses, where the need for energy implies more powerful systems with higher volumes of energy over shorter periods of time [5].

An important factor in the battery industry is the cost of batteries, and this is also a major factor in the field of second-life batteries, as the cost of a user device with certain diminished characteristics is also positively affected by the fact that the cost is discounted from the initial price. The authors of a comprehensive study on second-life batteries [8] suggest, after a critique of numerous papers, a cost of second-life batteries ranging from \$44 to \$180/kWh, which is more affordable than purchasing new batteries for these proposed secondary applications.

So far, this document has focused on the second life of batteries from EVs, as this is the largest market niche in which we can enter batteries with sizes and percentages of residual capacity suitable for these second-life applications mentioned above. We must also consider other types of the origin or first use of these batteries, like a storage battery system already installed and that, due to its use or disuse, the system no longer performs as it originally did, and its working capacity has been affected. This is our case, the Renewable Energy Development Centre (CE.D.E.R.) - Centre for Energy, Environmental and Technological Research (CIEMAT) located in Lubia (Soria, Spain). It is a public research organisation. This centre is part of the CIEMAT centre and is attached to the Department of Energy of the Spanish Government. The CE.D.E.R. specialises in the development and promotion of renewable energies associated with research projects in this field. For the development of all this work, it has different types of energy generation and storage systems.

One of the storage systems affected by this problem available at the centre is an LFP battery system. These LFP batteries consist of two racks of 627.3 V in total. For various reasons, the system has been in disuse for several years, which has had a notably negative influence on the system, greatly compromising its operation and, therefore, its performance.

Whether we are dealing with a battery system for primary vehicle or storage use, to assess its validity for a second use, it is necessary to examine the cells that make up the system and their capacities [8, 14].

Those batteries are known as "retired" and still maintain nearly 80% of their initial capacity after their first life uses [15]. Despite this, they are considered "out of service" as they cannot fully satisfy the demand established for the systems they were initially designed for. This aspect leads to the application of the concept of "second life", "reuse" or "recycle" into other different fields with demands of fewer current values involved or uninterruptable energy storage systems [16].

Concretely, LFP batteries have a useful period between

500 and 3500 cycles. When cells reach 80% of charge from their initial capacity, it is considered out of the range of the storage systems for which they were designed (currently EV) [17]. However, after the initial 2000 cycles of these batteries, their residual capacity can be 4 or 5 times higher than in the case of any acid battery (lead, sulphuric acid).

It is estimated that LFP batteries still can have around 2000 more cycles in second-life applications until their capacity is reduced to 60% and the loss of voltage is enough to consider the end of this second period of life [17].

From an economic aspect, these applications are attractive, given the fact that their cost is reduced to minimum values if we consider the price of a new battery, as well as a useful extended period of life. The first step in the investigation of LFP batteries and their life cycles is aging them and knowing their capacity and their behaviour against changes in charging and discharging processes, which bring the answer to whether they are valid or not for different energy storage systems and why. This represents the principal aim of this document.

These applications are directly related to the energy sources they are connected to, which has a strong influence on the charge and discharge conditions. Deep charging and discharging processes deplete battery life very quickly, while those partial charging and discharging processes extend this period [18]. This document is based on the paper "Second life for LiFePo4 batteries as an energy storage system in a smart microgrid" presented at IV Iberoamerican Congress on Smart Cities (ISCS-CITIES 2021). Throughout this document, we present a study of the selection and integration of a bank of LFP batteries into the CE.D.E.R. microgrid to give a second life to those cells in optimal working conditions after a period of disuse. The rest of the paper is divided into different sections: Section 2 represents the description of the storage system, Section 3 involves the jobs carried out for the recovery of the system, and Section 4 explains in detail the integration of the battery system on a smart microgrid for a second application. Finally, the conclusions obtained are presented and the bibliography is cited.

2. Material and methods

CE.D.E.R. has an electrochemical storage system based on LFP batteries, composed of 2 racks with 14 modules and 14 cells in each module, making a total of 392 cells. The operation of the system is completed with a grid three-phase inverter Ingecon Sun 30 (30 kW at 400 V AC and 50Hz) that can work with each of the racks independently, or with both at the same time.

This storage system was installed in 2012 and was involved in a research project in CE.D.E.R. with the aim of making it able to supply high-power energy during short periods of time (less than 1 hour).

Once the project was completed, and after several years of non-use, an objective was proposed, which was to put the system back into operation and integrate it into the CE.D.E.R. smart microgrid as an energy storage system.

In this case, the purpose of the system is completely different from the initial one, as instead of working with high-power energy supplies for short periods of time, (30 kW for a maximum of 1 hour), the current main objective is to work with lower power energy supplies for longer periods of time (4-8 kW for a few hours).

When starting with the process we call battery recycling (same components but for different end use), we face a process where we only have the basic cell and rack specifications that you can see in Table 1 and Table 2 without their charge and discharge curves and efficiency.

Table 1 Cell specifications

Cell technology	Lithium Iron Phosphate (LFP)
Nominal Voltage	3.2 V
Min. Voltage	2.0 V
Max. Voltage	3.8 V
Capacity	50 Ah
Nominal Energy	160 Wh
Nominal Energy (discharging C2)	167 Wh
Nominal Energy (discharging C3)	176 Wh
Nominal Power	160 W
Max. Power	640 W

Table 2 Rack specifications

Cell technology	Lithium Iron Phosphate (LFP)
Cells Number	196
Modules Number	14
Nominal Voltage	627.2 V
Min. Voltage	529.2 V
Max. Voltage	729.1 V
Capacity	50 Ah
Nominal Energy	31360 Wh
Nominal Power	31360 W
Max. Power	125400 W

To use those batteries as an energy storage system for the microgrid, it is essential to work on two different fields. On the one hand, the recovery of the damaged cells or those that have suffered a decrease in their efficiency as a consequence of the passage of time and their first use application. On the other hand, it is necessary to work on the communication system and its integration on the

CE.D.E.R. microgrid.

3. Cells recovery

For the recovery process of the storage system, we always refer and work at the cell level, as the average voltage values of the modules can falsify the individual voltages and, thus, compromise certain cells to the system as a whole.

In addition to knowing their voltage and, therefore, their state of charge, first of all, we must know their physical state, so that we can establish an initial classification of cells (suitable – unsuitable) to continue with the process depending on whether they have swollen, suffered a rupture or are structurally damaged.

To do this, all cells are removed from the two racks and visually assessed, leaving only those cells that have not suffered visible damage in the process. These will go on to the next stages of recovery.

The next step in the storage system reuse process is to check the capacity of each cell in the storage system. It is necessary to take note of the voltage level of each cell to estimate its State Of Health (SOH) with respect to its nominal voltage. These measurements are used for grouping similar cells in voltage and applying the same criteria for cells belonging to the same group.

This group division is carried out with its own criteria, taking into account significant values in the cells and in the system such as: minimum voltage above which the BMS does not recognise the cell (2.0 V), nominal cell voltage (3.2 V) and maximum cell voltage (3.8 V) defined by the manufacturer.

Another aspect that influences the definition of the groups is the number of cells with similar voltage values. When noting down the individual voltage values, it can be seen that quite a few cells have the same voltage value. This leads to the definition of groups with different amplitude ranges in order to be able to group cells that are as similar in voltage as possible and therefore behave similarly. The highest voltage found was 3.3 V, and the lowest, 0 V.

Taking into consideration the above, the 392 cells that compound the system are classified into 5 groups, depending on their voltage levels:

- 31 Cells with a voltage higher than 3.3 V.
- 86 Cells with a voltage between 3 and 3.3 V.
- 107 Cells with a voltage between 2 and 3 V.
- 121 Cells with a voltage between 0.5 and 2 V.
- 47 Cells with a voltage of 0.0 V.

The Battery Management System (BMS) of the system does not detect cells with a voltage lower than 2 V, as that corresponds to the minimum level established, and it is considered that cells with a lower level are damaged and not useful for this purpose. For this reason, it is necessary to raise the voltage of those cells with other methods to make the BMS able to recognise them.

In the process of charging the cells and increasing their voltage, a charger is necessary. In our case, we used a Revolectrix GT-500. It allowed us to charge and discharge up to 6 cells of several types (different kinds of lithium batteries, NiCd, NiMH and Lead Acid batteries) simultaneously.

The charge/discharge process is user-defined. It sets the current at which the process is carried out (with a limit of 20 A for charging and 8 A for discharging process) and the voltage limit at which the process ends. The voltage and current of the battery can be seen at any given time via the display. However, generally, chargers (as in this case) are not able to recognise voltage levels lower than 2 V in LFP batteries. That is why it is necessary to connect these cells to a power supply, so they can achieve a recognising voltage level and, after that, charge them until a voltage close to the nominal level. By way of this method, we make those cells that initially had a voltage between 0.6 and 2 V convert this level until the nominal voltage (3.2 V). On the other hand, the 47 cells with a level of 0.0 V could not be recovered and were thrown out from the experiment.

Cells with a voltage higher than 2.0 V can be detected by the BMS. Those cells between 2.0 V and 3.0 V are charged with GT-500 until their nominal voltage, while those with a charge higher than 3.0 V are not manipulated.

After a few days of rest, it is observed that in many of those cells with voltages between 0.6 and 2.0 V, their voltage level falls again until levels under 2.0 V. This means that they were not going to be recognised by the BMS and they are thrown out as well. The rest of the cells that initially were between 0.6-2.0 V and 2.0-3.0 V also lost some of their voltage levels but without reaching a level lower than 2.0 V.

To know the functioning of cells in each group, they are subjected to processes of charge and discharge with the GT-500 charger to study their behaviour.

3.1 Cells charging process

To study the current state of charge on the different cells, it is selected one of each group, a new cell (cell 1), a cell with a charge between 3.0-3.3 V (cell 2), a cell between 2-3 V (cell 3) and another with a voltage less than 2 V (cell 4).

The first step is fully discharging the four cells, to make them be in a similar initial state of charge and, after that, subject them to a process of charge at 8A (with a limited voltage of 3.6 V for the four cells). The results are the following:

Cell 1: This is the case of a new cell that represents the correct operational behaviour of a LFP battery and works as a reference to compare the state with the rest of the cells. Its voltage starting point is 3.05 V, and at least 380 minutes to achieve the 3.6 V scheduled in the charger as the maximum voltage.

In approximately 15 minutes, the cell has converted the initial 3.05 V until 3.26 V. In the following 280 minutes, close to 5 hours later, it produced a constant increase in its voltage until achieving 3.4 V. The next 30 minutes, the cell suffers again a quick increase of the voltage until 3.6 V. Finally, the cell maintains its level (3.6 V) for a while. After stopping the process of charge, the voltage starts to decrease its level until it stabilizes itself at 3.34 V.

Cell 2: At the beginning of the study, this cell had a voltage level of between 3-3.3 V. This level is considered right for the charge. During the process, it is observed 3 phases, as in cell 1, but with some differences.

The starting point is similar to cell 1 (3.06 V). In this case, the first phase of charge is shorter than in case 1 (13 minutes) and rapidly achieves a voltage slightly higher than the case before (3.27 V). In the second phase, where the increase is slow and progressive, the time involved was 250 minutes approximately, until achieving 3.52 V. Finally, the last phase lasts 20 minutes and the voltage is rapidly increased again, until achieving the 3.6 V scheduled in the charger.

The time involved in achieving 3.6 V is 280 minutes, a notable difference if we compare it with the 380 minutes with cell 1.

When the charge is finished, as in cell 1, the voltage level starts decreasing until it stabilizes after a couple of hours in a value close to the nominal (3.3 V).

Cell 3: At the beginning of this study, cell 3 had a voltage level of between 2 and 3 V. This range of voltage is a bit low. However, it is within the limits defined by the fabricant and understandable, considering that the system has not been used for a long time. Its behaviour is similar to cell 2, as can be observed in Figure 1.

Cell 4: This cell had a starting point at the beginning of the study lower than 2 V, at the limit of the voltage established by the manufacturer. This is a sign that the cell may not be suitable for recovery for a second life application.

As the starting voltage point is lower than 2 V (concretely 0.6 V) the charger cannot recognise it, so it is necessary to raise the voltage using the power supply until more than 2 V. By doing this, the charger can recognize the cell and start charging it.

During the first phase of charge, the voltage quickly rises to 3.24 V in 30 minutes. From this moment, its behaviour is similar to cell 1. Phase 2 lasts 240 minutes and reaches 3.4 V. Finally, in phase 3, the voltage level increases again quickly until 3.6 V. The total time involved in the charging process is slightly lower than in cell 1 (330 minutes).

This could lead us to the conclusion that, in contrast to what initially seemed, these cells could be reused in second-life applications. However, when the charge is stopped, the voltage levels decrease until values are lower than 2 V. This makes the systems unable to recognise them.

The summary of the results obtained is shown in Figure 1. The charging process is repeated with the same cells, but at different current levels to check if there are any differences. The results obtained lead to the conclusion that the behaviour is similar in all cases. Figure 2 shows the results obtained in a charging process with 16 A.

3.2 Cells discharging process

After charging the cells, they were subjected to discharging processes, limiting the voltage in the charger to 3 V, to compare the results. The initial current value of the discharging processes is 8 A.

The results obtained for the four cells are shown in Figure 3.

Cell 1: Discharging process starts with 3.34 V. In about 10 minutes, this level is decreased until 3.26 V, maintaining this value until almost 3 hours later. After this moment, the voltage decreases again, but much more quickly than before, until it achieves the 3 V scheduled in the charger.

The total time involved in the discharging process of this cell from the initial 3.34 V to 3 V was 360 minutes. When the discharge was stopped, and after hours, the cell slightly increased the voltage to 3.2 V.

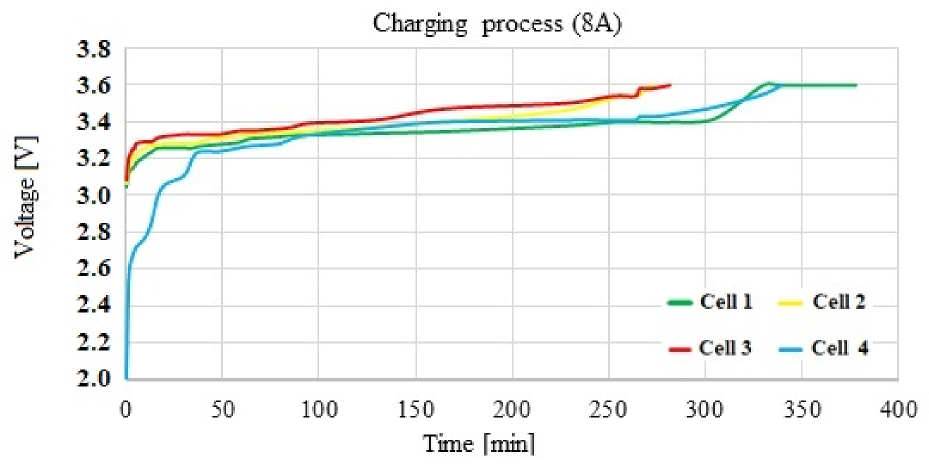

Figure 1 Cells charging process with GT-500 at 8 A

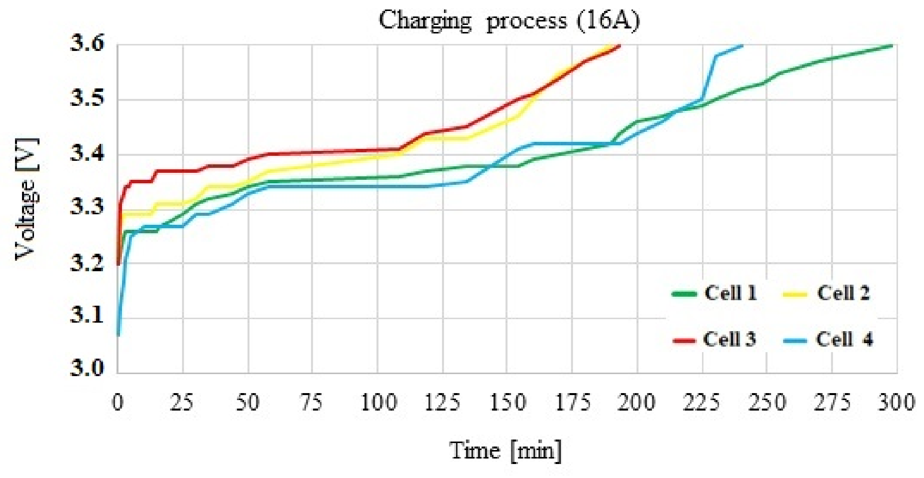

Figure 2 Cells charging process with GT-500 at 16 A

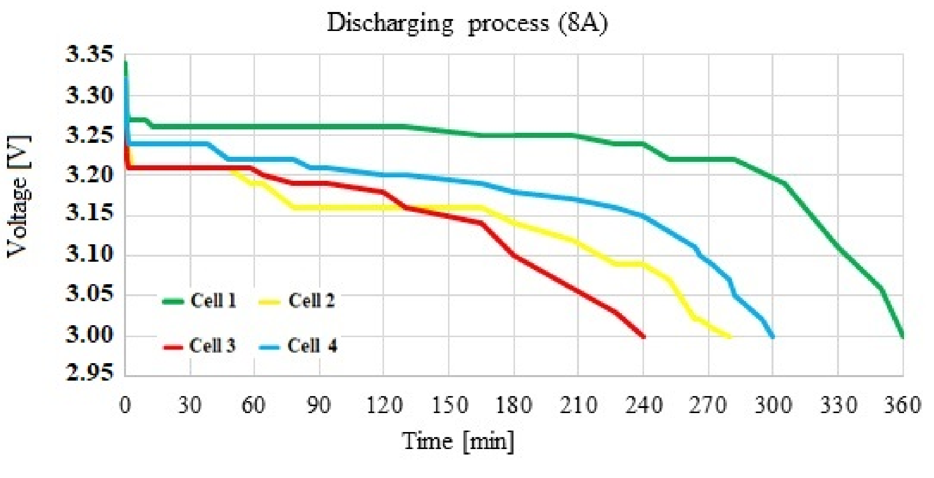

Figure 3 Cells discharging process with GT-500 at 8 A

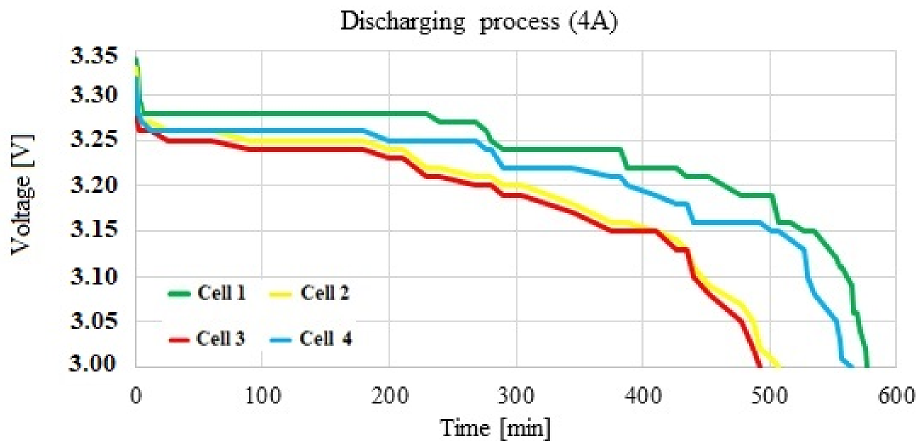

Figure 4 Cells discharging process with GT-500 at 4 A

Cell 2: Initially, this cell had a voltage of 3.32 V. This level is a bit higher than cell 1. The voltage was decreased in a few minutes until 3.21 V and maintained in that value for almost 1 hour. After that, it goes down to 3.16 V, staying at that value for more than 1 hour. From that moment, the voltage starts decreasing quickly until 3 V.

In this case, the total time involved was 280 minutes approximately. When the discharge finished, as occurred in cell 1, the voltage value of the cell achieved its nominal value.

Cell 3: As in the charging process, the discharge of cell 3 is like cell 2. However, there are some differences related to its bad conditions. A clear example of this is the time involved in the process, 240 minutes.

Cell 4: The total time involved in this cell was 300 minutes, less than cell 1 but higher than cells 2 and 3.

In phase 1, its voltage changes from the initial 3.32 V to 3.24 V in less than 5 minutes. This value is maintained for almost 2 hours and after that, it starts decreasing more quickly until 3 V.

In this case, the nominal value it achieves once the cell is not connected to the charger for some time, is enough evidence to demonstrate that the cell is not working properly. As it happened during the charging process, once disconnected, the nominal value increases (up to 3.1 V), but instead of stabilizing, it starts falling as time passes. The discharging process is repeated with the same cells at different current levels to check if there are any differences. The behaviour is similar in all cases. Figure 4 shows discharging process at 4 A.

3.3 Cells selection

Considering the results obtained in the sections of this document, it is demonstrated that the best options for second-life applications are those cells whose behaviour is like 2 and 3; otherwise, 4 is not.

Apparently, cells like 4 have a better capacity and could be used during long and continuous processes of charge, given the fact that if there are not long periods where the voltage falls, the cells work correctly. However, when they are in long periods of time without the charger connected to them, the voltage falls significantly. This can lead to a voltage lower than 2 V, which means that they are not going to be recognised by the system anymore.

On the one hand, cells 2 and 3 have worse charging capacity, but on the other hand, they can keep constant voltage levels without being connected to the system; meaning that, from a functional point of view, they work better for our purpose. That is the reason why they are selected to take part in the system. Once the best cells were chosen to take part in the energy storage system formed by the 196 batteries necessary in each rack, the next step is integrating them into the system of the microgrid.

4. Second life. Integration of the energy storage system in the microgrid

In order to integrate the energy storage system with LFP in the microgrid of CE.D.E.R., it is necessary to run out the next tasks:

- Establish the communication between the management app of the smart grid at CE.D.E.R. (developed with Home Assistant) and the control system of batteries (BMS-Battery Management System) to know the information about cells and regulate the power supply of charges and discharges with the converter.

- Once the communication is established, it is necessary to develop a SCADA inside the management software to control the operation of the batteries, so they could be managed manually with the microgrid operator.
- Finally, it is necessary to establish the automation, so the strategies of energy management, defined by the grid administrator, can be applied automatically without the need for an operator.

4.1 Communication with the management system and batteries control system

The control system is formed by many different elements:

- BMS of each module: Each of the 14 modules of a rack has a BMS that allows keeping under observation the voltage and temperature of each o of the 14 cells of each module. This BMS carries out a cell calibration during its charge and controls the fan to keep the system cool. The communication between the BMS of the rack is carried through by means of a CAN bus.
- BMS of each rack: keeps the voltage and temperature of the 14 modules that take part in each rack under observation. It also calculates the state of charge and the health conditions (SOH-State of Health) of each module. It establishes the communication with BMS of the system by means of the CAN bus.
- BMS of the system: keeps under observation the voltage and temperature of the two racks that make up the system. It leads the Modbus-RTU to communicate with a computer, where the software for the control of the storage system is installed.

The management app for the microgrid can communicate with BMS of the system using the protocol of Modbus communication in two different ways:

- Connecting a computer/Raspberry/Arduino etc., to the cable RS485 of the BMS of the storage system with a SCADA. This allows to monitor the information by way of a Modbus-RTU communication protocol, and after that, the management app of the microgrid must communicate with the SCADA to receive the information.
- Using a Modbus RTU-TCP/IP converter. A Modbus RTU (RS485) connects the exit of the BMS to the entrance of the converter. At the same time, the RTU-TCI/IP converter is connected to the microgrid's data network, thanks to a RJ45-Ethernet cable. In this way, the software can communicate directly with it. The SCADA allows to monitor the information and it has been developed with the same managing app as the microgrid.

The first option presents some disadvantages that make the second one much more interesting. On the one hand, by using Modbus RTU, only one device at a time is allowed to communicate; whereas by using Modbus TCP/IP, it is possible to communicate with more than one device at the same time. On the other hand, connecting the RS485 of the BMS to a device (pc, Raspberry or Arduino) is more expensive and complex than an RTU-TCP/IP converter, as it would be necessary to have two different SCADAs. One of them for the monitoring of the BMS and the other, for the development of the control system of the microgrid, to receive that information.

Also, apart from the communication with BMS of the energy storage system, the control system of the microgrid has to communicate with the converter, so the transmission of the data of charging and discharging processes is possible, as the BMS only produces the information about the batteries state, but does not allow its charge and discharge.

The converter allows communication by means of Modbus TCP/IP, so it can be connected to the data grid Ethernet of the microgrid. The control software can also directly communicate with it once the parameters are defined.

Figure 5 shows a diagram of communications of the control system in the microgrid with the energy storage system and the converter [19].

Once Modbus is established as a way of communication with the BMS of the system as well as with the converter of the grid, it is necessary to define the equipment in the configuration of the software used for the management of the system. In this case, the managing software is carried out with Home Assistant, software developed in Python. Despite it being used generally for home automation, it is a good solution for the monitoring and controlling of the microgrid in real time.

To establish communication, it is necessary to define both elements. On one side, the BMS of the system and, on the other side, the converter to grid in the configuration file. To do this, it is necessary to know the communication protocol (Modbus TCP), IP direction of each element and the connection link (which generally is 502 for Modbus TCP).

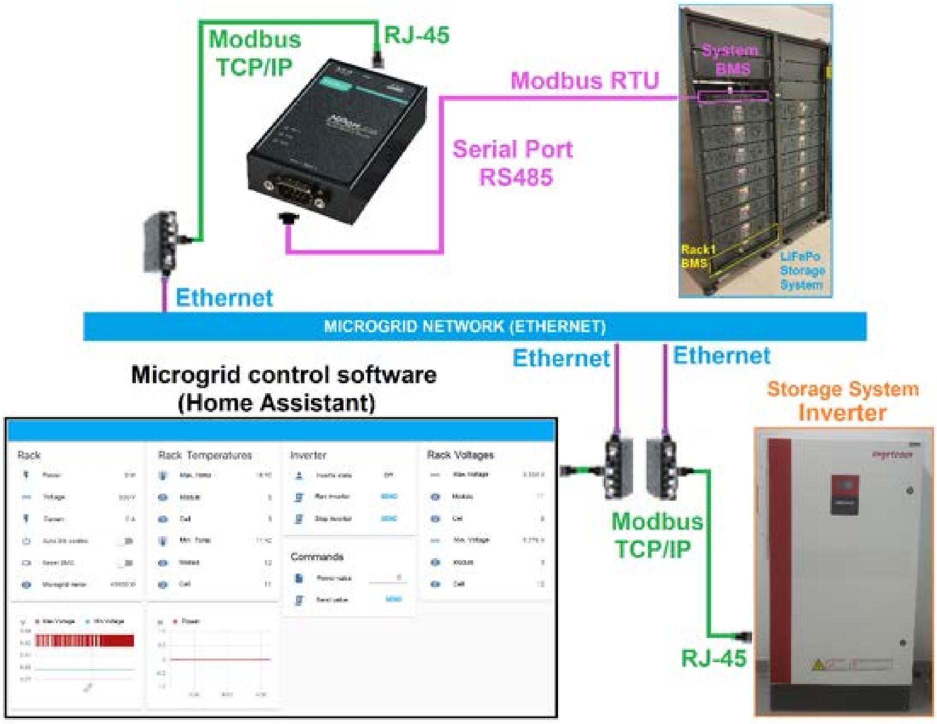

Figure 5 Communications diagram

```
-name: BMS_sistema_LFP      # name (BMS)
type: tcp                   # type of Modbus (RTU o TCP)
host: 192.168.15.102        # BMS IP address
port: 502                   # communication port
-name: inversor_red_LFP     # name (Inverter)
type: tcp                   # type of Modbus (RTU o TCP)
host: 192.168.15.90         # Inverter IP address
port: 502                   # communication port
```

Once the elements of the configuration file are defined, it is necessary to read the desired Modbus directions and to know the plot of each Modbus equipment. In the case of the BMS, it is not possible to send codes to it, as it only provides information about the state of the system; therefore, in order to monitor, only reading the direction is necessary. Examples are the temperatures and the voltage of cells. All this is defined with the configuration file of Home Assistant in the following way:

```
- platform: Modbus                      # Modbus
scan_interval: 1                        # monitoring interval
registers:
- name: Tensión_maxima_célula           # variable to monitoring
hub: BMS_sistema_LFP                    # hub previously defined
register_type: input                    # type of register (input,
                                        holding, etc.)
unit_of_measurement: W                  # unit_of_measurement
slave: 1                                # identification number
register: 44                            # Modbus address
count: 1                                # number of address
scale: 1                                # scale (x1, x10, etc.)
```

Regarding the inverter, apart from reading the parameters like voltage, current values, and power supply for its monitoring (defining them in the configuration file), it is also necessary to send codes to carry out the charging and discharging processes in the specific conditions (previously defined). This is done by means of a script:

```
potencia_inversor_litio:            # script name
mode: single
sequence:                           # sequence of commands
- data:
address: '1000'                     # Modbus address
hub: inversor_red_LFP               # hub previously defined
unit: '1'                           # identification number
value:
- 8                                 # Defined value to battery charge
                                    /discharge
- sensor.consigna_potencia          # charge/discharge power
service: modbus.write_register
```

The last step in the integration of the storage system is the creation of a control panel (interface) with Home Assistant. This allows visualising the parameters in real time, monitoring the BMS of the system and the converter, and sending codes for charging and discharging the batteries intuitively.

Using Home Assistant is very easy to develop this interface. The starting point is a frame that allows inserting the cards with many different functions. It is possible to add cards with all the values registered in the configuration files.

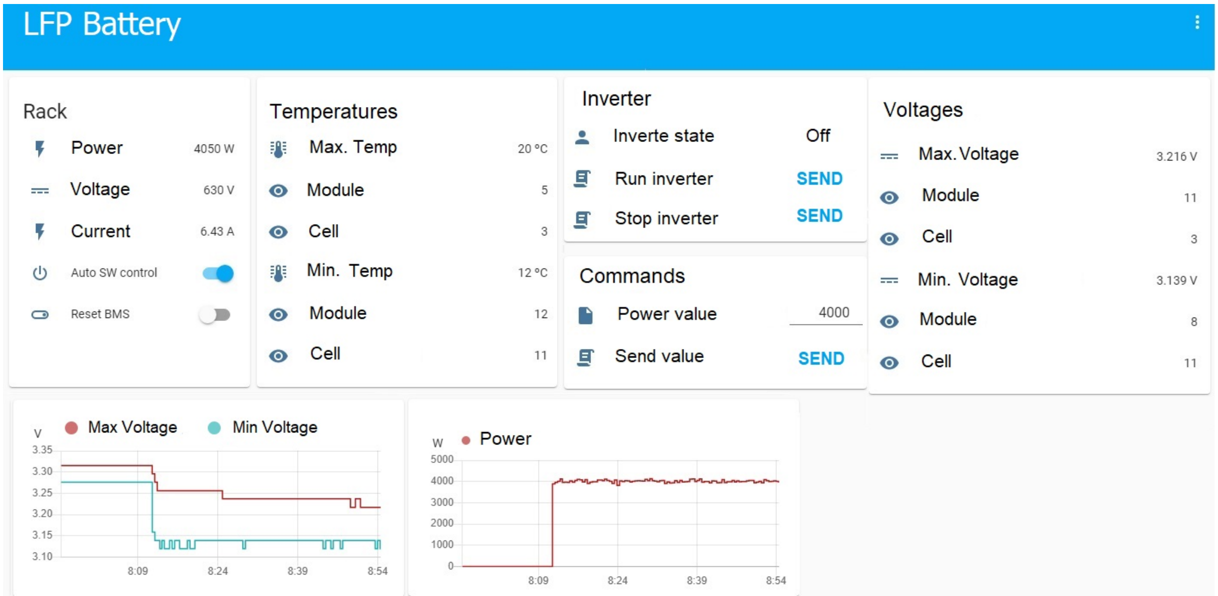

Figure 6 Control panel in Home Assistant

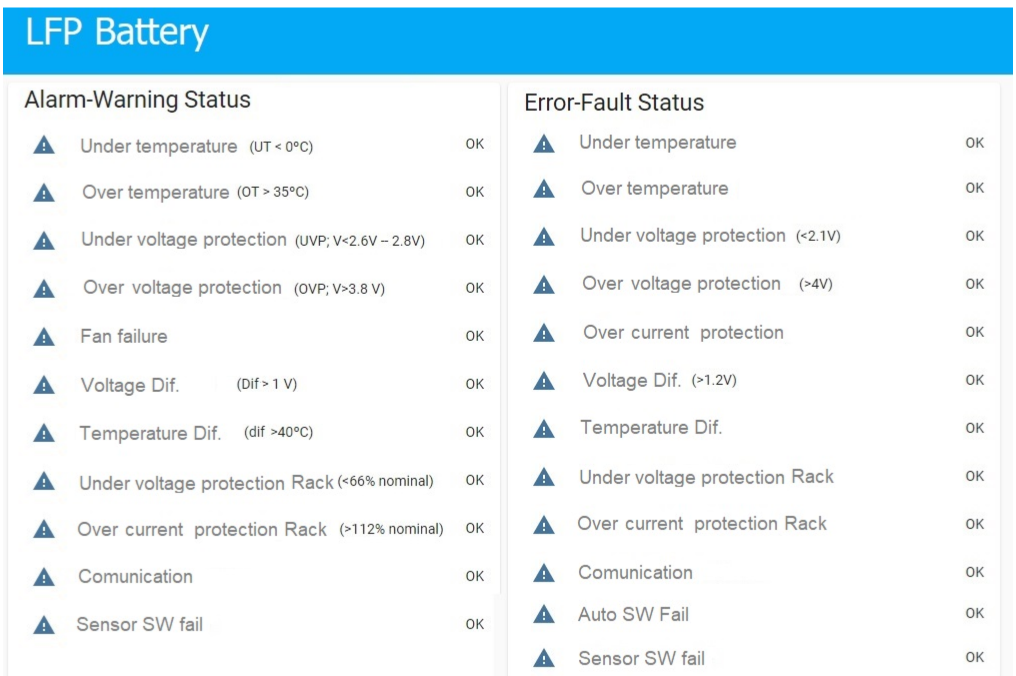

Figure 7 Battery errors

This can be a numerical or historic graphic. Figure 6 shows the control panel of the storage system during the process of charge of the batteries. Figure 6 shows a 4-kW discharge process. The system voltage is 630 V, and the batteries are providing 4050 W to the grid (current value 6.43 A). The average voltage at the rack is 3.198 V; with cell 3 of module 11 as the maximum (3.216 V) and cell 1 of module 8 as the minimum (3.139 V). The average temperature of the rack is 20 ºC. Also, it can be graphically observed that at the beginning of the discharge, the voltage of cells (the maximum and the minimum) slightly falls until achieving a value that is maintained for a long time during the discharging process.

Figure 7 shows the interface with the errors that can occur in batteries. In that moment, during the discharging

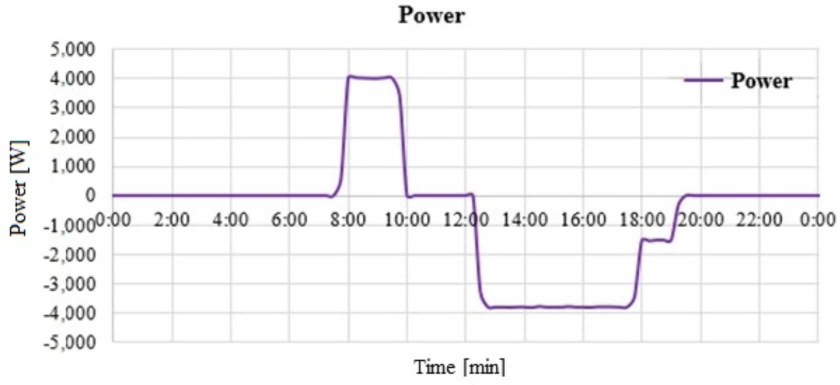

Figure 8 Charging and discharging process at 4 kW. Power

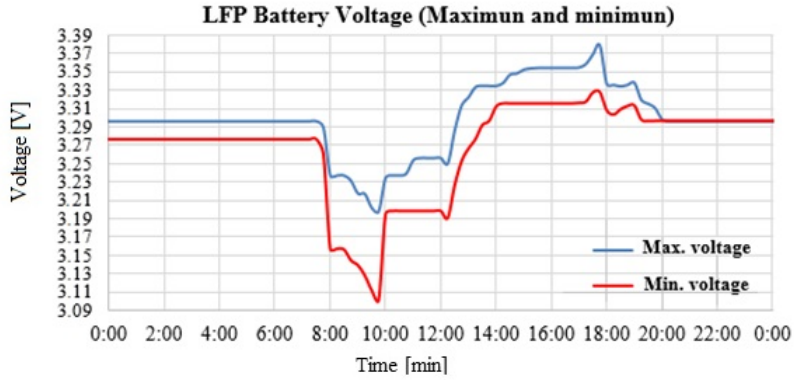

Figure 9 Charging and discharging process at 4 kW. Maximum and minimum voltage

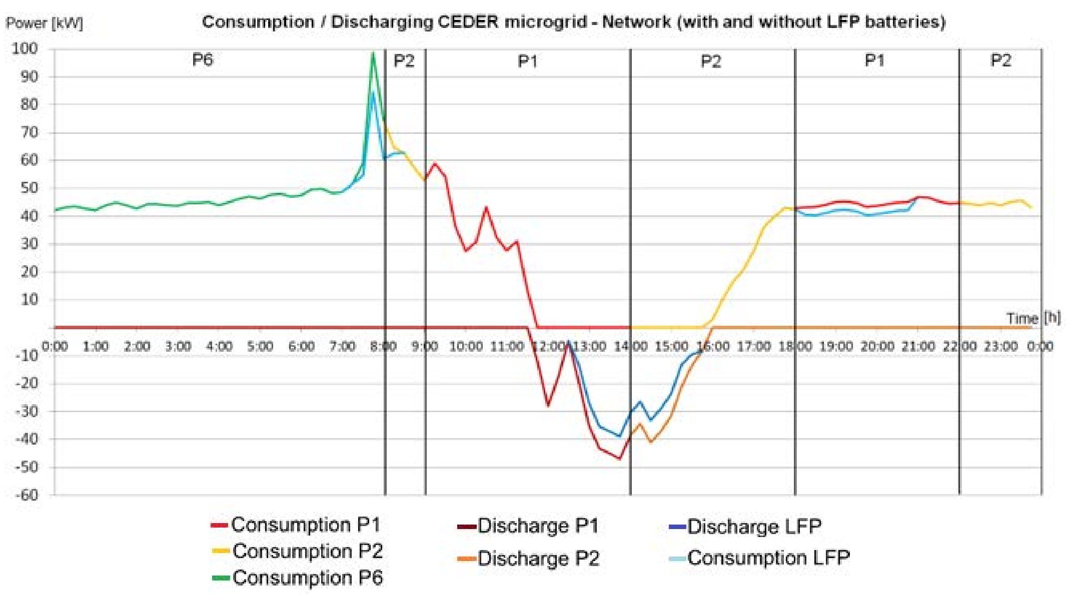

Figure 10 Consumption/Discharging CE.D.E.R. microgrid – Network (with and without LFP batteries)

process, there are neither alarms (Warnings) nor errors (Faults). The system notifies when the minimum voltage of the cell falls under the minimum working parameters.

Once the system is integrated into the LFP batteries system in the management app of the microgrid, it can be used as a storage system for a second-life application. This second life is under lower voltages than those that the system was initially created for.

Figures 8 and 9 show graphically the entire charging and discharging processes with a power value of 4 kW (the charging power supply is -4000 W and the discharging 4000 W). Figure 8 shows the power supply of the system, and Figure 9 shows the maximum and minimum voltage of the cells.

4.2 Operation of the recovered LFP battery system in CE.D.E.R.´s microgrid

This last section shows the operation and contribution of the recovered LFP battery system within the microgrid, taking into account the criteria for cell selection and integration within the monitoring and control system developed in the previous sections.

Thanks to the monitoring system that collects data from the batteries, we have been able to carry out an ex-post study of the system´s performance.

Figure 10 shows the operation of the microgrid versus the distribution grid with particular reference to the LFP batteries during a full day.

To better understand the graph and the influences of the incorporation of these LFP batteries into the CE.D.E.R. microgrid on the centre's electricity bill, we will explain how the current contract with the distribution network breaks down.

The centre has an electricity contract with an electricity distribution company on a commercial basis, which disaggregates the 24 hours a day into six different billing periods. The most expensive period is P1, and the cheapest is P6, with costs decreasing progressively from one to six.

The final costs for each period are broken down by different concepts, including the energy consumed during that period and the contracted power. If the consumption is higher than the contracted power for that period, an extra charge will be applied to the bill, so it is important to ensure that the power never exceeds the power detailed in the contract.

On the other hand, the only variable concepts in terms of quantity are related to energy: the more kWh consumed, the higher the electricity bill is. Conversely, the less energy consumed, the lower the amount. With these two aspects in mind, we shall look at the influence of batteries on the microgrid as a whole. The graph shows the operation of the microgrid in the centre versus the distribution grid for a full day. In it, we see three periods of battery operation. Two periods of discharge have helped to flatten the peak consumption and, therefore, reduce the energy consumed from the grid. And a battery charging period has contributed to reducing the discharge of surplus generation into the distribution grid.

Extrapolating these daily results to the rest of the year would be similar. We see that the operation and influence of the battery system in the microgrid of the centre fulfils the following functions:

Flatten consumption peaks during the first and last hours of the day. The periods coincide with the start of the working day and late afternoon when the generation decreases.

Reduce the discharge of surplus to the distribution network during the peak generation period of the day.

Reduce the cost of the monthly electricity bill due to lower consumption of active energy.

Consider reducing the contracted power to reduce the cost of this item on the electricity bill.

5. Conclusions

This paper explains the steps followed in CE.D.E.R. to give a second life to LFP batteries as an energy storage system in a smart microgrid, after not being used for their initial purpose for a long time.

After checking the initial state of health of each cell and studying their charging and discharging curves (V-t), those that performed the best were selected to make operational one of the racks. There were not enough cells to recover both racks because many of them were damaged.

Once one of the racks has been completed with the best-performance cells, the battery management system (BMS) and the inverter to the grid were integrated into the control system of CE.D.E.R.'s microgrid, allowing its use (second life) as the energy storage system of the microgrid.

In its second life, this battery system cannot put up with fast processes of charge and discharge with high power supplies, close to 30 kW (just a few minutes). However, it can work with lower power supplies (around 5 kW) for several hours, which is very useful in the energy management of the microgrid. These allow the storage of energy surplus from distributed generation systems (wind turbines and photovoltaic systems) and use that energy when needed, improving microgrid's efficiency.

Future work would be to recover the second rack by using the remaining cells and buying new ones to complete the total of 196 cells. This would double the storage capacity, in addition to improving the performance of the entire system by introducing new cells.

6. Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

7. Funding

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8. Author contributions

Conceptualization, O.I-M.; Methodology, O.I-M., P.P-C. and N.A.G.; Software, O.I-M.; writing—original draft preparation O.I-M. N.A.G. and P.P-C.; writing.

9. Data availability statement

Data were collected at CEDER-CIEMAT from May to September 2021. We used the BMS of the LFP battery systems and Ingeteam inverter, connected to CEDER´s both microgrid energy management control system developed with Home Assistant to measure power and voltage.

References

[1] M. H. Lee and D. Shang-Chang, "Allocative efficiency of high-power li-ion batteries from automotive mode (am) to storage mode (sm)," *Renewable and Sustainable Energy Reviews*, vol. 64, Jun. 02, 2016. [Online]. Available: https://doi.org/10.1016/j.rser.2016.06.002

[2] R. Tresa-Jacob and R. Liyanapathirana, "Technical feasibility in reaching renewable energy targets; case study on australia," in *4th International Conference on Electrical Energy Systems (ICEES)*, Chennai, India, 2018, pp. 630–634.

[3] P. peña carro, O. Izquierdo-Monge, L. Hernández-Callejo, and G. Martín-Jiménez, "Estudio e integración de pequeños aerogeneradores en una microrred periurbana," *Revista Facultad de Ingeniería*, vol. 104, Jul. Sep. 2022. [Online]. Available: https://doi.org/10.17533/udea.redin.20210845

[4] S. Nesmachnow, G. Colacurcio, D. G. Rossit, J. Toutouh, and F. Luna, "Optimizing household energy planning in smart cities: A multiobjective approach," *Revista de Ingeniería*, vol. 101, Act. Dic. 2021. [Online]. Available: https://doi.org/10.17533/udea.redin.20200587

[5] L. Paoli and T. Gül. (2022, Nov. 30,) Electric cars fend off supply challenges to more than double global sales, iea: International energy agency. [Online]. Available: https://tinyurl.com/mr2c8393

[6] M. H. S. M. Haram, J. W. Lee, G. Ramasamy, E. E. Ngua, S. P. Thiagarajaha, and *et al.*, "Feasibility of utilising second life ev batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges," *Alexandria Engineering Journal*, vol. 60, no. 5, Mar. 09, 2021. [Online]. Available: https://doi.org/10.1016/j.aej.2021.03.021

[7] E. Hossain, D. Murtaugh, J. Mody, H. M. R. Faruque, M. S. Haque-Sunny, and *et al.*, "A comprehensive review on second-life batteries: Current state, manufacturing considerations, applications, impacts, barriers & potential solutions, business strategies, and policies," *IEEE Access*, vol. 7, May. 20, 2019. [Online]. Available: http://doi.org/10.1109/ACCESS.2019.2917859.

[8] E. Martinez-Laserna, I. Gandiaga, E. Sarasketa-Zabala, J. Badeda, D. I. Stroee, and *et al.*, "Battery second life: Hype, hope or reality? a critical review of the state of the art," *Renewable and Sustainable Energy Reviews*, vol. 93, Apr. 14, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2018.04.035

[9] J. Neubauer and A. Pesaran, "The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications," *Journal of Power Sources*, vol. 196, no. 23, Jun. 15, 2011. [Online]. Available: https://doi.org/10.1016/j.jpowsour.2011.06.053

[10] Q. Liao, M. Mu, S. Zhao, L. Zhang, T. Jiang, and *et al.*, "Performance assessment and classification of retired lithium ion battery from electric vehicles for energy storage," *International Journal of Hydrogen Energy*, vol. 42, no. 30, Jun. 06, 2017. [Online]. Available: https://doi.org/10.1016/j.ijhydene.2017.06.043

[11] V. V. Viswanathan and M. Kintner-Meyer, "Second use of transportation batteries: Maximizing the value of batteries for transportation and grid service," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 7, Jun. 23, 2011. [Online]. Available: http://doi.org/10.1109/TVT.2011.2160378

[12] R. Reinhardt, I. Christodoulou, S. Gassó-Domingo, and B. Amante-García, "Towards sustainable business models for electric vehicle battery second use: A critical review," *Journal of Environmental Management*, vol. 245, May. 23, 2019. [Online]. Available: https://doi.org/10.1016/j.jenvman.2019.05.095l

[13] C. S. Ioakimidis, A. Murillo-Marrodán, A. Bagheri, D. Thomas, and K. N. Genikomsakis, "Life cycle assessment of a lithium iron phosphate (lfp) electric vehicle battery in second life application scenarios," *Sustainability*, vol. 11, no. 9, Apr. 28, 2019. [Online]. Available: https://doi.org/10.3390/su11092527

[14] Y. Jiang, J. Jiang, C. Zhang, W. Zhang, Y. Gao, and *et al.*, "State of health estimation of second-life lifepo4 batteries for energy storage applications," *Journal of Cleaner Production*, vol. 205, Sep. 17, 2008. [Online]. Available: https://doi.org/10.1016/j.jclepro.2018.09.149

[15] F. Salek, S. Resalati, D. Morrey, P. Henshall, and A. Azizi, "Technical energy assessment and sizing of a second life battery energy storage system for a residential building equipped with ev charging station," *Applied Sciences*, vol. 12, no. 21, Oct. 31, 2022. [Online]. Available: https://doi.org/10.3390/app122111103

[16] H. C. Hesse, M. Schimpe, D. Kucevic, and A. Jossen, "Lithium-ion battery storage for the grid—a review of stationary battery storage system design tailored for applications in modern power grids," *Energies*, vol. 10, no. 12, Dec. 01, 2017. [Online]. Available: https://doi.org/10.3390/en10122107

[17] P. Cicconi, D. Landi, A. Morbidoni, and M. Germani, "Feasibility analysis of second life applications for li-ion cells used in electric powertrain using environmental indicators," in *2012 IEEE International Energy Conference and Exhibition (ENERGYCON)*,

Florence, Italy, 2012, pp. 985–990.

[18] H. A. Catherino and F. Feres, "Consequences of deep cycling 24 volt battery strings," *SAE International Journal of Alternative Powertrains*, vol. 4, no. 2, Jul. 2015. [Online]. Available: https://www.jstor.org/stable/26169097

[19] O. Izquierdo-Monge, P. Peña-Carro, R. Villafafila-Robles, O. Duque-Perez, A. Zorita-Lamadrid, and *et al.*, "Conversion of a network section with loads, storage systems and renewable generation sources into a smart microgrid," *Applied Sciences*, vol. 11, no. 11, May. 26, 2021. [Online]. Available: https://doi.org/10.3390/app11115012