Smart Charging Station with Photovoltaic and Energy Storage for supplying Electric Buses

Alberto Berrueta
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
alberto.berrueta@unavarra.es

José J. Astrain
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
josej.astrain@unavarra.es

Guillermo Puy
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
isc@unavarra.es

Ismail El Hamzaoui
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
isc@unavarra.es

Alfredo Ursúa
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
alfredo.ursua@unavarra.es

Pablo Sanchis
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
pablo.sanchis@unavarra.es

Jesús Villadangos
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
jesusv@unavarra.es

Francisco Falcone
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
alberto.berrueta@unavarra.es

Antonio Lopez-Martin
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
antonio.lopez@unavarra.es

Ignacio R. Matías
Institute of Smart Cities
Public University of Navarre
Pamplona, Spain
natxo@unavarra.es

***Abstract*— A Smart Charging Station (SCS) has been installed in the Public University of Navarre, Spain, in the framework of the H2020 Smart City Lighthouse STARDUST project. The SCS consists of a high-power electric bus charging point (300 kW), a 100 kW photovoltaic system, a 84 kWh support energy storage system based on a second-life lithium-ion battery, and a monitoring and control system that allows the safe storage and convenient access to operation data. This SCS operates as a Smart Grid, being able to provide the power peaks required by the electric bus charger, reducing and smoothing the power demanded from the distribution grid and increasing the renewable energy self-consumption rate. This contribution presents a novel monitoring and control system, which is a key tool to integrate this SCS in the data infrastructure of a Smart City, as well as an energy management system able to operate the SCS to achieve the above-mentioned technical requirements. The crucial role of the monitoring and control system and the energy management system becomes evident in this work.**

Keywords—smart city; smart grid; electric bus; monitoring; lithium-ion battery, second-life battery

I. INTRODUCTION

The main objetive of the Smart Cities and Communities Lighthouse STARDUST project [1] is the development and implementation of new technologies that contribute to modernizing current cities and moving towards more efficient, intelligent, sustainable, and essentially citizen-oriented cities. Within the project, seven cities collaborate to test and validate technical solutions and innovative business models, as well as deliver blueprints for replication throughout Europe and abroad. Some of the most important areas in the project concern mobility, efficient energy and information and communication technologies (ICT). Particularly, the electrification of the urban public transportation is critical to improve, among others, air quality and noise pollution in cities. In addition, electric buses are associated to improved comfort and more comprehensive information for users [2].

However, the adoption of such electric buses presents relevant technical challenges related to the power grid. The short time available for the battery charging at terminal stops entails high-power peaks demanded from the grid [3]. To cope with this problem, a photovoltaic battery self-consumption system [4] has been installed at the Public University of Navarre, thereby building the Smart Charging Station (SCS) presented in this contribution.

This paper includes two relevant contributions to overcome these challenges. On the one hand, a novel monitoring and control system is presented that makes it possible the implementation of smart energy management strategies to control the charging and discharging of the second-life Li-ion battery. Moreover, a safe storage of the operation data is performed with the presented monitoring system, and a notification function is included to interact with the users. The data access and representation in dashboards is also tackled, and the architecture of the control and monitoring system is designed to make it integrable in a Smart City data

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environment. On the other hand, the design of an energy management system (EMS) is a main challenge in the design of an SCS [5, 6]. We propose in this contribution a novel EMS that tackles the above-described technical challenges. Three performance indicators are defined to compare the proposed EMS with a base case. The results are validated by means of simulation, the EMS is programmed in the SCS and the experimental results of the SCS operating with the proposed EMS are shown in order to prove the technical feasibility of the monitoring, control and energy management systems proposed.

The remaining of this contribution is structured as follows. Section II shows how the electrification of public transportation affects the quality of the power distribution grids and describes the route of the electric buses that run since 2019 in Pamplona, Spain. Section III describes the Smart Charging Station, along with the proposed control and monitoring system. Section IV details the proposed energy management strategy, and Section V presents simulation and experimental validation. Finally, the main conclusions and future work are described in Section VI.

II. IMPACT OF ELECTRIC BUSES IN THE DISTRIBUTION GRID: DEPLOYMENT OF SMART GRIDS

The promotion plans to reduce the number of combustion vehicles and progressively move towards an electric and sustainable transport are experiencing a constant update in their figures that anticipate a rapid transition towards a system based on electric mobility. This is in line with the constant reduction in prices, the latest technical improvements on electric vehicles and the increase in energy density of batteries [7]. Although the electrification of transport is beneficial in all its variants, it is crucial to achieve smart and sustainable cities. Electric vehicles offer improved air quality, noise pollution reduction, lower energy consumption and, if electric energy is obtained from renewable sources, energy independence.

In this context, public transport plays a key role, given its high utilization factor and number of passengers per vehicle. The development of the charging infrastructure to optimally integrate future electric public transport systems requires the consideration of particular characteristics of these systems: known routes and controlled frequencies, but whose charging at charging stations can cause problems in the power distribution networks of cities [8]. In addition, advanced monitoring and communication systems are required for an optimal operation of the global electric bus networks, as shown in [9]-[11].

Since March 2019, Route 9 of public transport in the city of Pamplona, Spain, is totally operated by electric buses in a groundbreaking initiative. This route connects two terminals, one located at the Arrosadia Campus of the Public University of Navarra (UPNA) and the other one at the Train Station. Now, the route is covered by six electric buses that depart every 12 minutes from the two terminals and run the 12.3 km distance of the go and return trip. The buses have a 44.3 kWh lithium titanate (LTO) battery, with a rated voltage of 650 V and a weight of 550 kg. Each terminal has a fast-charging point, typically used in public transportation where the buses must be quickly charged during the stopping time. Fig. 1 shows the pantograph of the UPNA fast-charging point when is operating and connected to one of the buses. The average energy consumption per trip has been estimated at some 10 kWh and the bus has about 3.5 minutes to charge again its battery.

Fig. 1. Bus fast-charging point at UPNA.

As mentioned in the introductory section, one of the most important challenges for the deployment of urban electric bus fleets is their electricity supply. The power peaks demanded by the charging stations can compromise the quality of the city power distribution network and cause voltage drops and perturbations. A good example is the charging station at UPNA, where buses can demand charging peaks of around 250 kW, a value considerably higher than the average power consumed, that can be lower than 70 kW.

III. DESCRIPCIÓN OF THE UPNA SMART CHARGING STATION

A. Power components

The Smart Charging Station (SCS) used for the design of the Energy Management System (EMS) is represented in Fig. 2. It is built by the following three elements:

- The fast-charging point with a rated power of 300 kW, connected to the utility grid through a 340 kVA transformer.
- A 135-kWp photovoltaic system, with a nominal power of 100 kW, installed on the roof of UPNA's teaching building. This PV system is meant to supplement the fast-charging station energy needs.
- An 84-kWh second-life Li-ion battery built up by 192 modules extracted from Nissan Leaf electric vehicles. This battery is the energy storage system that allows the energy management of the SCS.

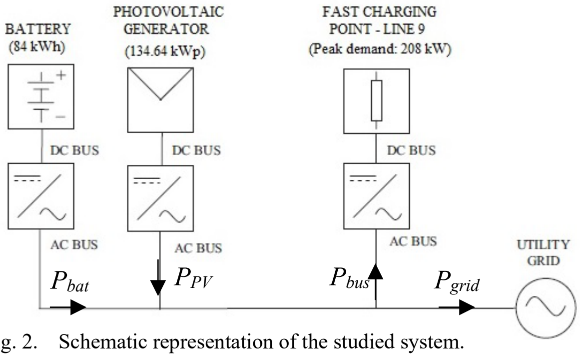


Fig. 2. Schematic representation of the studied system.

B. Monitoring and Control System

In order to include the EMS in the SCS, a unified monitoring and commanding system is mandatory. This system is designed, as detailed below, with the aim of presenting useful, quality, and effective information to the user. Therefore, appropriate data models are selected to allow not only the collection and organization of information consisting of data and context, but also its understanding by humans who need to use them for other purposes. In this sense, following the Smart Data Models Initiative [9], the monitoring system implements the schema, the specification, and the payloads. The schema is the technical representation of the model and includes the definition of both data types and data structures. Data structures are a means of handling large amounts of data efficiently, while data types ensure a homogeneous and interoperable format of the information.

The architecture of the designed monitoring and control system is shown in Fig. 3. System data from weather station, PV inverter, battery inverter, battery BMS and wattmeters is gathered by means of a Message Queuing Telemetry Transport (MQTT) data gathering system based on Mosquitto. The generated queue is normalized by means of a Telegraf system, which also allows a bidirectional communication via Telegram with the user. Afterwards, the normalized data is stored in an InfluxDB time series database. The design of this architecture is due, on the one hand, to the rapid ingestion of data from various sensors, and on the other hand, to the temporal nature of the information. This database allows the use of graphing tools such as Grafana [10] or Kibana [11] and, in addition, the use of deep learning APIs such as Loud ML [12] to define, train, and deploy machine learning models for predictive analytics.

The data sources included in the SCS presented in this contribution are interconnected by means of a private and wired network (Ethernet). Each data source sends data to the MQTT broker Eclipse Mosquitto [13]. Up to 180 monitoring variables are gathered by the MQTT broker every second. An asynchronous collection mechanism is chosen with the aim of storing the records as fast as possible. MQTT allows this task to be performed in an agile and efficient way following the publish-subscribe paradigm. By using this paradigm, the measuring instruments can limit their function to send the measurements in due time and form to the broker, while the broker organizes the appropriate workflows with the collected information. Thus, the broker sends information to each subscriber. The main subscriber in our case is the storage system (InfluxDB), although a complementary flow is defined when required by the control system programmed in a Siemens PLC.

The operation of the Telegraf agent [14] is schematically represented in Fig. 4. The agent collects the metrics from the MQTT broker. As Telegraf uses in-memory metric buffers, metric collection is granted even if the database is temporarily unavailable. On the one hand, this Telegraf agent sends the metrics to the Influx DB and, on the other hand, manages these metrics for the notification of alerts and alarms through Telegram. InfluxDB and the data scripting language Flux allow the creation of custom and powerful notification rules, which can be integrated using chat bots from the Telegram instant messaging tool to send the real-time alerts and alarms to the user's smartphone, as shown in Fig. 5.

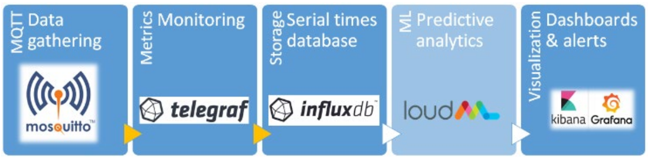


Fig. 3. Monitoring system architecture.

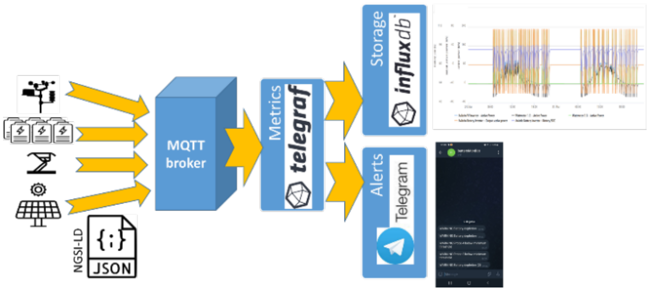
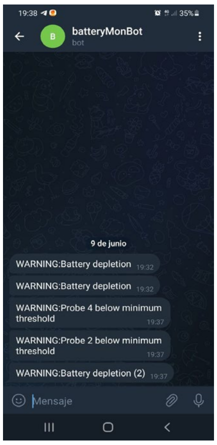


Fig. 4. Alarm notificaction by means of Telegram chat bots.

The Influx DB is stored in the UPNA data centre. This database guarantees a suitable and safe data storage, and thanks to a dashboard based on Grafana provides a convenient and fast access to the desired data, as shown in Fig. 6.

The SCS control is made by means of a SIMATIC Target 15000S from Siemens. This PLC is also connected to the LAN network described before and is able to send commands of real and reactive power to the PV inverter and battery inverter. Thanks to the combination of the Siemens programming tool TIA Portal and the compiler of Matlab Simulink, the SIMATIC PLC offers a convenient programming interface. The PLC is programmed for a 1 Hz measurement of the system variables, while the commands are sent at a frequency of 1.25 Hz in order to decouple reading and writing operations.



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WARNING:Battery depletion 19:32

WARNING:Battery depletion 19:32

WARNING:Probe 4 below minimum threshold 19:37

WARNING:Probe 2 below minimum threshold 19:37

WARNING:Battery depletion (2) 19:37

Fig. 5. Example of Telegram chat bot.

Fig. 6. Exemplary representation of 5 of the stored variables during two days of system operation.

IV. ENERGY MANAGEMENT SYSTEM FOR THE SCS

A. *Objectives of the energy management system*

The energy management proposed in this contribution is the algorithm designed to compute the power command sent to the second-life battery converter. This battery charging or discharging command is computed to achieve two technical objectives, which also include an economical perspective. The first technical objective consists of a reduction in the power peak demanded from the grid by the SCS. This is a power-intensive application of the second-life battery, given that high power peaks are required during short times. With this aim, the SCS contributes to improve grid stability by reducing the peak power and the power fluctuations demanded from the grid. Therefore, such energy management strategy allows the installation of SCS in areas with weak power grids unable to handle high power peaks or fluctuations, or alternatively an increased number of SCS connected to a given power grid. The economical perspective of this first objective comes, firstly, from the reduced cost of the contracted power, given that the peak power is reduced. Secondly, this strategy allows a smaller sizing of various components of the SCS, such as the network connection and transformer. Thirdly, the installation of additional SCS should be considered for the profitability analysis.

The second technical objective of the energy management system is an energy-oriented target consisting of an augmented self-consumption rate. By means of the proposed EMS, the use of the PV power generated at the SCS is used more effectively, thereby reducing the carbon footprint of the system, the power demanded from the grid and therefore the electricity bill. Conversely to the first objective, which leads to a power-intensive use of the second-life battery, this second objective consists of an energy-oriented use, given that a small number of deep charges and discharges are remanded from the battery. Previous studies concerning EMSs in Li-ion batteries highlight the interest of such combination of power- and energy-intensive services to enlarge battery usability [15].

The proposed EMS is analyzed by means of the following performance indicators in order to assess the fulfillment of the main objectives.

- *P+*: the maximum power absorbed by the SCS from the grid.
- *RatioPV*: the percentage of the load energy demand met by the photovoltaic system.
- *BatteryEOL*: the expected battery end-of-life (in years). This is calculated based on the state-of-charge profile of the battery under the energy management strategy and a state-of-the-art aging model [16, 17].

These are the three performance indicators that are calculated in the following subsections of the contributions to compare the proposed EMS with a base-case algorithm. The comparison is made possible by means of the safe and reliable data monitoring and control system described in the previous section.

B. *Energy management strategy*

The block diagram of the proposed energy management strategy is presented in Fig. 7. It is based on the variable P_{net}, which is defined, based on the powers presented in Fig. 2, as:

$$P_{net} = P_{PV} - P_{bus} \tag{1}$$

This P_{net} is the variable that ideally should be managed by the battery. However, given the limited size of the battery, only high frequencies are tackled. Therefore, this variable is filtered by a 33-minutes SMA filter. Moreover, a control of the average battery SOC is added to prevent continuous charging or discharging of the battery and keep its SOC around 90%. This average SOC is computed in the same time window of 33 minutes used for the moving average of P_{net}. The additional power due to the average SOC control is:

$$P_p = k_c \cdot (refSOC - SOC_{avg}) \tag{2}$$

where *refSOC* is the reference value around which the SOC wants to be kept, *SOCavg* is the measured SOC filtered with the 33 minutes SMA, and k_c is the proportional constant for the control loop. A swipe analysis is performed to compute a suitable value for k_c. The selected value for the studied SCS is $k_c = 0.113$ kW/%.

V. SIMULATION AND EXPERIMENTAL RESULTS

After designing the strategy, it was tested in Matlab by means of the real data measured in the SCS and recorded in the InfluxDB database. An annual simulation is required to compute the performance indicators introduced in Section IV.A. Given that the database has been recording data for less than a year, an extrapolation is made to make annual simulations. The main results of these simulations are shown in Fig. 8.

The results of the three performance indicators achieved by the proposed strategy, in comparison with the base case, with no EMS, are compiled in Table I. This table shows an 18% reduction of the maximum power demanded from the grid and a 16% increased self-consumption ratio. However, based on the datasheet of the second-life battery, and state-of-the-art aging models, the estimated lifetime of the battery subject to this operation characteristics is as low as 2.2 years. This analysis leads to the conclusion that the economic feasibility of a second-life battery for this kind of applications needs to be carefully analysed.

In order to assess the technical feasibility of the second-life battery for this EMS, the PLC control and monitoring system described in Section III has been used to control the SCS by means of the proposed EMS during three weeks of operation. The measured results are similar to those expected from the simulation, thereby proving the technical feasibility of the proposed control and monitoring system, as well as second-life batteries, for this application. A relevant issue detected during the experimental validation are the short peak surges in the variable P_{grid} due to the fast ramps demanded by the bus charger shown in Fig. 9. Due to the sampling time of 1 second used by the data monitoring system, these fast ramps cannot be compensated by the battery. Fig. 9 shows four

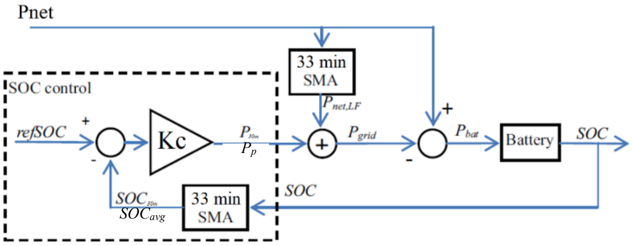

Fig. 7. Energy management strategy of the SCS.

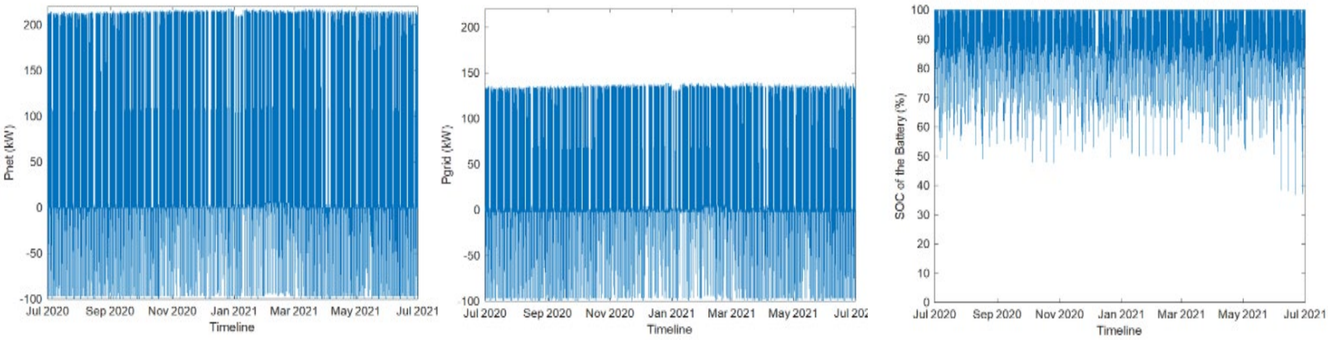

Fig. 8. Simmulation results of the proposed strategy: (a) Power demanded from the grid in the base case (no EMS), (b) Power demanded from the grid using the proposed EMS, and (c) State of charge of the battery during the year.

charges of the bus, where the peak surges are clearly visible. Therefore, if these short peak surges are a problem to the power grid, the system would need to be further analysed, either by improving the control strategy to increase its dynamic response, or by reducing the ramp rate demanded by the charging station. Given that the power rising time is not a critical variable for the fast-charging station, the second approach might be the most suitable one in most cases.

VI. CONCLUSION

This paper shows initial results of the operation of a Smart Charging Station at the Public University of Navarre, installed in the framework of the STARDUST project. The SCS, which operates as a Smart Grid, consists of a support stationary battery, a photovoltaic system and a monitoring and control system. It is an example of how these installations can contribute to the deployment of a vast public electric bus network in Smart Cities, avoiding the disturbance of the distribution power grids. The proposed control and monitoring system, as well as the energy management system, guarantee a correct operation of the second-life batteries and present useful information to the user, while having the capability of being integrated in the city data platform. For further similar installations, the suitability of second-life batteries needs to be carefully analysed, due to the fast aging induced by the aggressive cycle profile demanded by the SCS.

TABLE I. Performance indicators of the proposed EMS.

	P+ (kW)	ratioPV	Battery EOL
Base case	218	15%	-
Proposed EMS	139	31%	2.2years

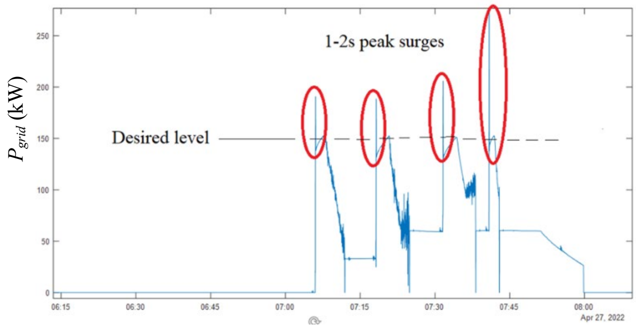

Fig. 9. Power peak surges detected during the experimental validation of the enery management strategy..

In addition, this Smart Charging Station has a relevant potential in terms of education and scientific dissemination. In fact, it is a tool to study different energy models, to assess the feasibility of different configurations and to foresee the impact of different events and situations. Thanks to its location in a university and to the informative dashboards designed by means of Grafana, it has the potential to disseminate the increasing potential of electrical mobilities in cities among general population and among future professionals and engineers.

The future research work planned for this project is to focus on the predictive analysis offered by Loud ML based on artificial intelligence techniques. Knowing the time series to be modelled, the model date ranges are set, Loud ML builds the models, and saves them in the desired InfluxDB database for convenient analysis and visualization. The first step would be to build a smart data model and a learning model. These two models would be fed by the data stored in the above-described database, thereby starting the inference process by means of Tensorflow [18] and Keras [19]. The use of Loud ML would allow the detection of abnormal dips in battery performance, anomalous battery loads, manage the battery to extend its lifetime, would provide forecast capacity of power demand based on weather and historical demand, as well as perform predictive maintenance.

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