32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19-22, 2019

Performance monitoring and optimization of an electric vehicle charging station

G. Fernández[1], M.A. Oliván[1], J. Sediles[1], J. Sanz[2], J. Almajano[1], J. Bruna[1], A. Muñoz[1]

[1] *CIRCE Foundation. C/ Mariano Esquillor Gómez, num 15, 50018 Zaragoza (España). gfa@fcirce.es, maolivan@fcirce.es, jsediles@fcirce.es , jalmajano@fcirce.es, jbruna@fcirce.es, amunoz@fcirce.es*

[2] *Electrical Engineering Department. CIRCE-University of Zaragoza, Zaragoza, Spain. jfsanz@unizar.es*

Executive Summary

Combustion vehicles are responsible for a great part of the pollutants generated worldwide and electric vehicles (EVs) are proposed as a solution. Besides its benefits, the spread of EVs will increase energy consumption and uncontrolled recharging could produce critical demand peaks. This paper describes a microgrid able to mitigate EV grid impact. The proposed control system coordinates distributed storage and renewable sources with an EV charging station. Following this idea, hardware and software tools were developed within FLEXICIENCY Project to monitor and optimize economically the operation of a charging station equipped with a solar photovoltaic generator and a storage system.

Keywords: EV (electric vehicle), microgrid, optimization, energy storage, IoT (Internet of Things).

1 Introduction

Road transport vehicles, globally are responsible for 24% of CO_2 emissions, being this sector one of the few that maintains an upward trend [1]. This sector is also the main producer of NO_x (50%), CO (25%) and particles PM2.5 (10%) [2] [3]. Another important aspect in which internal combustion engine (ICE) vehicles impact is in the economy of the countries. According with EUROSTAT, in 2016, Europe imported 549.9 Million tons of fuel oil (87 % of total consumption) and in the case of Spain, imports reached 99% of domestic fuel oil consumption. In Europe 48% is used for road transport with a sectorial dependency of 94 %.

As recognised by the European Commission (EC), electrification of transport, with electric vehicles and pluggable hybrid electric vehicles (EV and PHEV), is the key to reduce environmental impacts [4], in conjunction with decarbonisation of electricity production. On the other hand, to prevent negative impacts of a massive EV penetration on the electricity grid, EV recharging needs to participate in Responsive Demand Schemes. In [5] it is shown that power demand and road mobility demand are both characterized by two peaks (morning and evening). Morning peaks allow very good coordination, suggesting that overnight charging of EVs minimizes the need for incremental electricity generation capacity and investment in distribution infrastructure upgrades. However, evening peaks show that the increase in energy demand is a risk for the network, which would require an important investment in additional capacity, if demand management is not introduced. Demand management consists basically in shifting charging times. The objective can be multiple, such as optimization of the network infrastructure, avoid increase of generation capacity, optimization of renewable energy integration (avoid curtailments and increase penetration). Most of the proposals to achieve these objectives focus on time-of-use (TOU) rates [6][7] or real-time pricing (RTP) [8][9]. Going one step further, controllable EV charging (V2G) can be considered as valuable network asset, providing flexibility services. Exploiting the possibility of using them as energy storage [10] [11] [12], they can provide ancillary services such as synthetic reserve, voltage and frequency regulation.

In this framework, the activities carried out in the Spanish demo of FLEXICIENCY Project [13] involved the creation of new services for retail market and e-mobility. In particular, in the use case of Tabacalera Building EV charging station in Málaga (UC-5, Use Case, identification coding in the project) [14] a microgrid composed of a photovoltaic generator, lead-acid batteries and consumption points (charging points and auxiliary demands) was converted into a system that works in a coordinated and optimized way to support the electric grid operation.

To show the work carried out, this paper is structured as follows: section 2 shows the physical lay-out of the charging-point microgrid, section 3 describes the global management structure, chapter 4 and 5 describe main characteristics of local and remote systems. The last section lists first operational results validating correct behaviour of the solution, provides an outlook of possible improvements that can be easily added to the solution and the main conclusions of the paper.

2 Initial charging station

The starting point has been an existing microgrid completely composed by commercial components (see Figure 1) whose operation was not optimised. The main components are:

- 15 kWp solar PV generator using SMA STP15000TL solar inverter
- 1500 Ah lead-acid batteries at 48 V connected to the microgrid through SMA SI 8.0H converter
- Sensor Box, equipped with different environmental sensors that monitor solar irradiation and wind speed, and Web Box, to which the different elements are connected through the ModBus RTU serial communication protocol, both from SMA
- Several electric vehicle charging points, from 5 to 15 kW, single and three-phase

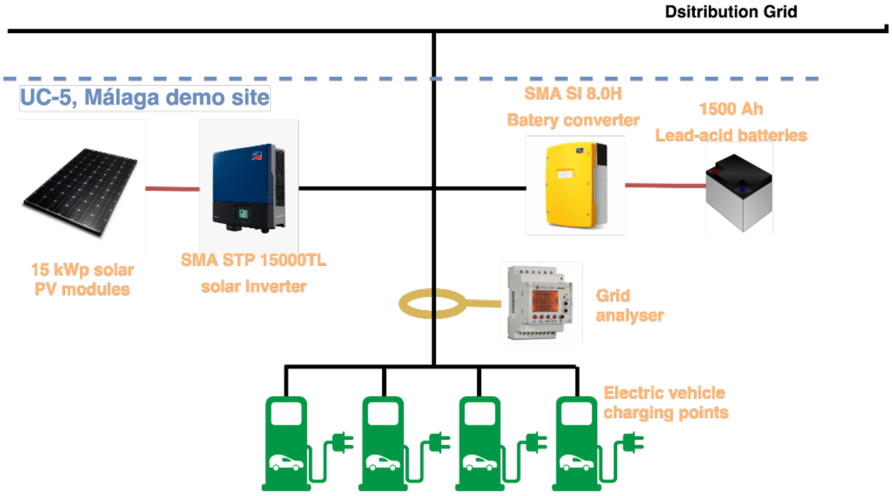

Figure 1. Microgrid schema.

All components operated in an independent way:

- PV inverter only generating active power (MPP tracking), injecting excess power into the grid
- Energy storage system only for back-up: If the grid fails, stored energy feeds EV charging points

The visualization and control interface of the inverters and the sensors was carried out with a proprietary development of the SMA equipment. It is accessed via a web browser where the behaviour of the different elements is monitored and parameterized.

3 Management structure

The hardware and software tools developed, deployed and tested can be separated in two groups: local systems and remote systems (see Figure 2). Grid analysers, solar photovoltaic inverter, weather sensors, battery converters, SMA Sunny WebBox and CIRCE Energy Box (and advanced gateway) are the local system components, used to monitor and manage the microgrid and are deployed at the demo site in Málaga. The CIRCE Web Server, operating outside if the demo site hosts the remote system.

Local systems have two main functions: (1) monitor the microgrid to provide field measurements to the remote system and (2) apply operation set points to battery converters, previously adapted to the real demo-site conditions. The Energy Box is connected to:

- Grid analyser monitoring demand of EV charging points and auxiliary consumptions
- Sunny WebBox monitoring and operating solar PV inverter, weather sensors and battery converters

The Energy Box exchanges information with the **remote system** (CIRCE Web Server), providing monitoring data and receiving operation setpoints.

The main objective of the CIRCE Web Server is to calculate set points for the field devices that minimize the energy bill of the charging station.

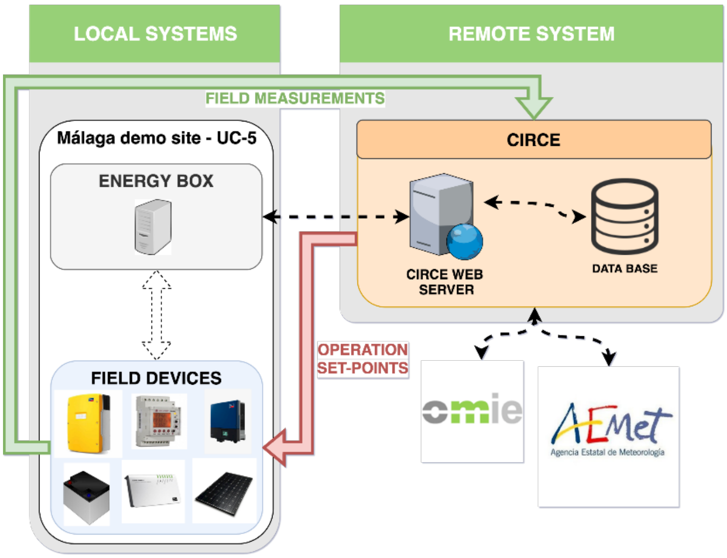

Figure 2. Global operation schema of the deployed solution.

A 4-G router has been installed to create a local network between the EB and the WebBox and to connect the EB with the control centre through the internet. Besides, the EB is connected to a grid analyser and the SMA WebBox using ModBus RTU protocol. Communication with SMA devices is done through the SMA WebBox system (see Figure 3).

Measurements from microgrid devices are collected by the EB and sent to the remote control centre using a MQTT communication protocol, where it is stored in a database. Obtained data are used to calculate an optimized operation plan for each device for the next 24 hours (divided into 15-minute intervals). This plan is sent to the EB and updated every 15 min. MQTT protocol is a secure protocol as it requires uthentication and verficiation among different application layers and allows the use of different security certificates. It works with Secure Socket Layer (SSL) and Transport Layer Security (TLS) to provide a security layer between client and server.

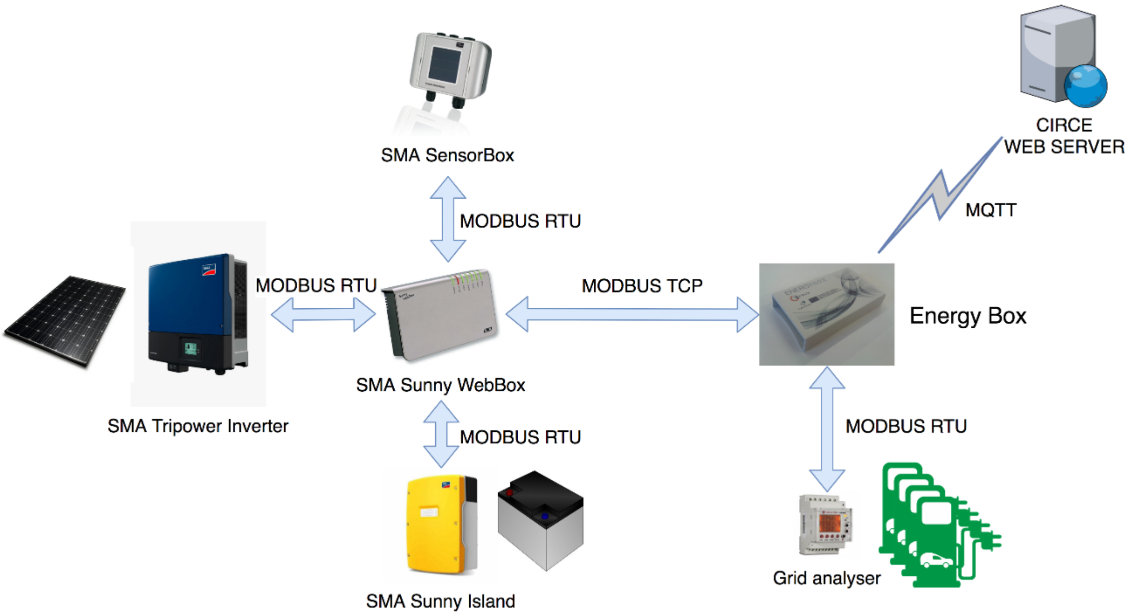

Figure 3. Communications schema.

4 The Energy Box – CIRCE's IoT hardware solution

To monitor and operate all the components of the charging station a device called "Energy Box" (EB) has been installed. The EB has been developed by CIRCE for micro-grid management. It is a multi-purpose concentrator for the operation of advanced electrical networks and Smart Grids. In addition to its versatile communication capabilities, it contains an embedded computer that provides computing and processing capacity to implement distributed computing: capture and storage information, execution of algorithms and control of the installation among others.

The EB has different physical communication interfaces: Ethernet, serial connectors and Wi-Fi. The core is based on a Raspberry Pi for industrial environments, suitable for multi-tasking and robust to electromagnetic noise. The architecture is divided into two blocks: communication and management.

The management block is responsible for gathering all system information for further processing, in addition to performing real-time management of the system. For this management, local algorithms are implemented to convert 15-min setpoints from the optimized program (calculated at the control centre) to real-time set points for each controlled device in a time step of 10 seconds. The programming language used is ADA, specific for critical systems with very strict temporal requirements.

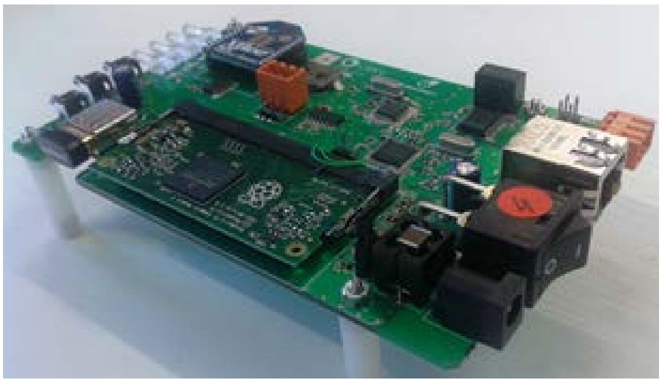

Figure 4. View of the PCB of the Energy Box (left image) and complete set with enclosure (right).

4.1 Hardware description

The Energy Box is the result of an ad-hoc hardware design complying with project requirements regarding communication capabilities and algorithm processing. Size and enclosure are suitable for a smart-home application. The Energy-Box v2.0 is a printed circuit board (PCB) that includes different functional parts. Its main characteristics are:

- Dimensions: 140x90mm
- Board copper thickness: 35x35x35x35um, standard value
- FR4 as base material
- Four layer board to distribute the signals in an optimal way and reduce the size
- Surface Mounting Devices (SMD) both, on top and bottom layers and Through Hole Devices (THD) on top layer

The EB is a versatile development that includes five communication standards (ZigBee, USB-Wi-Fi, Ethernet, RS232 and RS485) and a µSD Card slot for external storage. Therefore, the PCB is divided into 6 functional modules, which communicate with the core module, as shown in Figure 6. Green elements can be managed by the manufacturer and the user, while orange ones are factory programmed.

Every module has different layout restrictions that are critical for correct hardware performance and in consequence, their position on the layout is clearly defined. Most importantly, the design prevents operational interferences.

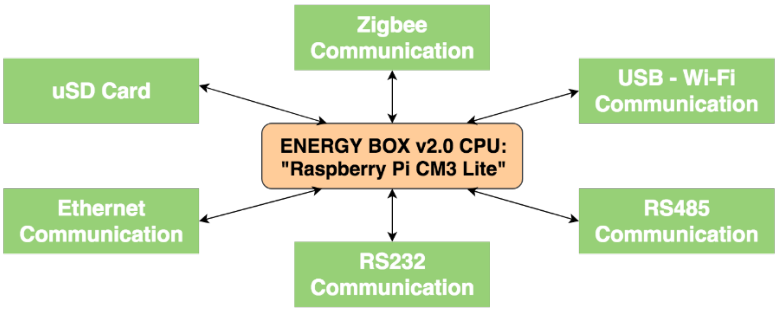

Figure 5. PCB functional blocks.

4.2 Software description

The chosen operating system to manage all hardware described earlier is Raspbian-Linux given its known advantages regarding availability of device drivers and customizability. The default Raspbian-Linux comes with the device drivers for all hardware referred in the previous sections: LAN9512 (giving Ethernet and USB-Wi-Fi), FT2232D (RS323 and RS455), DS1307 (Real time clock via I2C). On the other hand, the operating system allows its customizability to the bare minimum to execute the control and communication program with the complete communication and security capabilities of a modern operating system minimizing superfluous tasks.

The Energy Box software runs profiting the aforementioned operating system capabilities. The latter hides hardware complexity and allows many communication channels to control devices and exchange information with remote systems and SCADAs. On the other hand, the Energy Box software design gives flexibility to configure monitoring and control of microgrid devices.

4.3 Local algorithms

As explained in section 5.2, the operation set points calculated by the remote system are based on forecasts. As forecasts are always more or less deviated from actual values, the EB adapts the set points to the real state of the microgrid. In this use case, the EB monitors the real solar PV production and demand from the EV charging points and modifies batterey charging/discharging set points trying to maintain the expected power at the grid connection point.

5 Remote System

The remote system accomplishes five main tasks:

- Receive and store information gathered by field devices and sent by the Energy Box via MQTT
- Execute a programmed task to calculate 15-min average values from local measurements and to fill slots with missing data
- Forecast the state of some microgrid components
- Calculate optimized operational set points and send them to the Energy Box every 15 min
- Provide remote access to local SCADA

5.1 Hardware description

Technical features of the remote system hardware environment are listed below:

- OS Windows 7 Enterprise
- Machine features:
    - Processor: Intel (R) Xeon(R) CPU E5-2650 v3 @ 2.30GHz (2 processors)
    - RAM: 12 GB
- App Container: Apache Tomcat 8.5
- Forecast and other algorithms: Matlab® executables
- Optimization algorithms: GAMS 24.8 running CPLEX solver
- App Remote Centre: Java 1.8

5.2 Software description

The software of the remote system consists of the CIRCE web server, which integrates external services for collection of energy prices (OMIE) and weather forecasts (AEMET) and collects measurements from field devices. In addition, forecasts and optimisation algorithms are calculated and sent back to the Energy Box. All data are stored in a dedicated data base. The information flow at the CIRCE Web Server is organised as follows (see also Figure 8):

1. Every 10 s the Energy Box sends measurements from field devices to CIRCE Web Server (via MQTT protocol) where they are saved in a Data Base
2. Every 15 min, a scheduled batch of tasks is executed:
    - 2.1. Calculate 15-min averages from measurements and complete time slots with missing data
    - 2.2. Retrieve external data from OMIE and AEMET (energy prices and weather data)
    - 2.3. Execute Matlab forecast algorithms using historical 15-min averages
    - 2.4. Create input table with all necessary data for optimisation
    - 2.5. Execute GAMS algorithm to calculate optimal operation of UC-5, using forecasts
    - 2.6. Save forecast and optimization results in the data base, and create historical log of all results
    - 2.7. Create a JSON structure from last optimization result and send it to EB using MQTT protocol
3. There is a specific function on the remote system in which the system sends the last calculated plan on request. This function is used when the EB is rebooted.

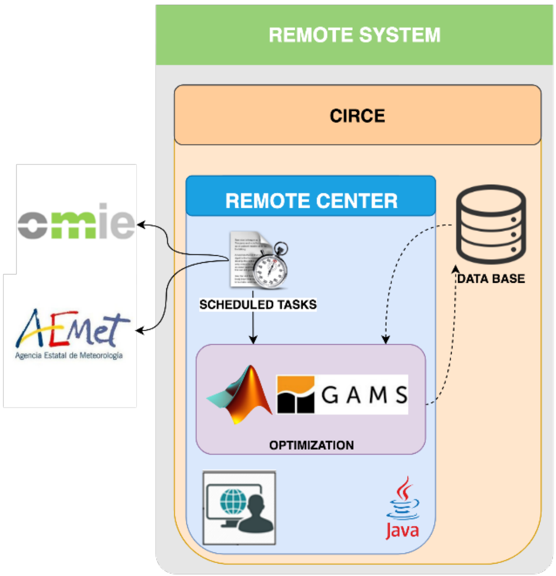

Figure 6. CIRCE web server calculation optimization plan.

The optimization algorithms calculate operation set points from the manageable devices of the microgrid, which in this UC is only the battery converter. The output is an optimized operation plan for the next 24h in 15-minutes steps which minimizes the energy bill of the microgrid. It should be mentioned, that the optimimization covers a horizon of 72 h, while the operation plan covers 24 h. The objective function is formulated as follows:

$$f = CV_{CS} + CV_{SS} + I + C_{PeajPss} + C_{Pss} \qquad (1)$$

Where CV_{cs} is the cost of energy purchased from the electric grid (at market price in the simulations), CV_{ss} is the cost of using the battery (related to the ageing derived from charging and discharging it), I is the income from selling energy to the grid (zero in the simulations), $C_{PeajPss}$ is the cost of grid access tolls (power price) and C_{Pss} is a penalization for high battery power (to reduce battery charging and discharging power and enlarge its life).

The introduction of a power price ($C_{PeajPss}$) in the objective function provides a means for reducing demand peaks, obtaining a peak-shaving feature without the need of defining a fixed maximum power limit.

Therefore, forecasts for expected demand, distributed generation (solar PV in this use case) and energy prices are needed as optimization model inputs. These forecasts are provided by executables developed in Matlab. A statistical forecast method based on historical data has been adopted, which outperforms more sophisticated models for short-term predictions (several hours) [15]. Energy prices are obtained from OMIE (Spanish electric market operator) and weather forecasts (for solar and wind predictions) from AEMET (Spanish weather agency) web pages.

In addition to the dynamic optimization, parameters described above, static parameters, such as storage characteristics, grid connection power, nominal device power, are introduced in the database and used in the optimization.

The resulting Quadratic Constrained Problem is formulated with GAMS software [16] and solved with CPLEX solver. The GAMS platform has been chosen because it provides a user-friendly environment for programming complex optimization problems. First results from the demonstrator have shown that the pair GAMS – CPLEX performs in a stable and efficient way for this use case.

5.3 Monitoring SCADA

The SCADA system is communicated with the EB software via RESTAPI providing a User Interface to the system. It uses the GNOGA framework in order to get modern web access in an Ada environment. The

SCADA allows microgrid monitoring by showing total energy balance and values of active and reactive power of the elements attached, battery SoC and voltage as well as weather data.

Figure 7. Example of SCADA main page: Grid Status.

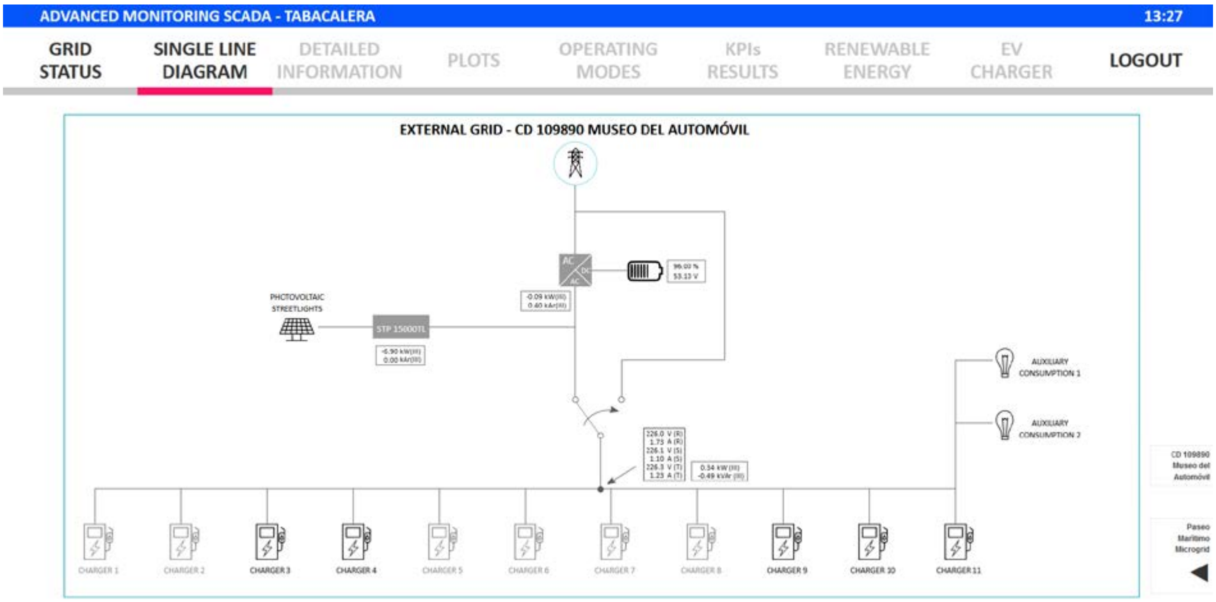

Figure 8. SCADA Single Line Diagram screen, showing detailed information of the main components of the microgrid.

6 Conclusions from first operational results

The main objective of the project was to demonstrate that the developed solution operates correctly regarding optimization algorithms and robustness of communications, which could be confirmed by first operational results. During November and December 2018 more than 95% of the time the remote system provided operation set points for the storage system. When the remote system did not provide updated set points, the local system operated seemlessly with the last available plan (24 h / 15-min steps).

In October 2018, more than 96% of the 10-second measurements arrived and were stored in the database correctly. It has to be highlighted that in that month maintenance and other tasks where carried out and generated some communication failures and even in this circumstances, the success rate of communications was very high. Therefore, it could be demonstrated that the solution, consisting of the remote system and Energy Box as communication gateway is robust and reliable.

Simulations carried out with real data from early October 2018 show that an optimized use of batteries can transform daily energy expenses into important income (selling excess energy during high-price hours). For example in the tested days the obtained income was greater than the expenses without using batteries. Another advantage is that reactive power is compenstated maintaining the power factor near unity at all times.

These benefits would be higher if the battery charger could work unbalanced, receiving different operation setpoints for every phase. It has been observed in real operation that the aforementioned benefits are reduced because the installed devices could not follow the set points exactly, as they operated in full kW steps. Finally, no energy from the batteries could be sold to the grid due to the Spanish legislation at that moment.

Besides the aforementioned operation, in another use case of the FLEXICIENCY project a flexibility offer operation mode has been implemented and could be applied also in this UC. The flexibility operation mode is based on the principle described in [17] and is used to calculate available flexibility of the microgrid to support the DSO in the operation of the electric grid. In addition to the options of remote operation, local operation modes can be implemented directly in the EB without any external device participation. These local operation modes could be: peak shaving, reactive power compensation and frequency/voltage regulation (following limits set by standards). These local operation modes, together with the flexibility mode can give further support the local DSO operating the distribution grid.

At the light of these first results, it can be concluded that the deployment of distributed storage and renewable energy systems is a solution to enable massive EV deployment avoiding grid congestion. This paper presents a package of hardware and software tools for monitoring and optimised operation of an EV charging station equipped with a solar PV generator and lead-acid batteries. The main hardware is CIRCE's Energy Box, which provides versatile communication capability. Software tools are implemented both, for remote and local operation. This two-level approach combines advantages of forecasting (remote) and real-time operation (local). The proposed monitoring and control system transforms an EV charging station in a distribution grid support asset with an optimised operation and the possibility to offer flexibility services to grid operators, but also autonomous operation thanks to distributed control.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646482.

Disclaimer

This paper reflects only the FLEXICIENCY consortium view and the European Commission (or its delegated Agency INEA) is not responsible for any use that may be made of the information it contains.

References

[1] International Energy Agency, "CO2 Emissions from Fuel Combustion 2017 - Highlights," *Int. Energy Agency*, vol. 1, pp. 1–162, 2017.

[2] International Energy Agency, "Energy and Air Pollution," *World Energy Outlook - Spec. Rep.*, p. 266, 2016.

[3] T. Longden, "Travel intensity and climate policy: The influence of different mobility futures on the diffusion of battery integrated vehicles," *Energy Policy*, vol. 72, pp. 219–234, 2014.

[4] P. Kyle and S. H. Kim, "Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands," *Energy Policy*, vol. 39, no. 5, pp. 3012–3024, 2011.

[5] "Global EV Outlook 2018. Towards cross-modal electrificationl."

[6] J. Zhang and T. Markel, "Charge management optimization for future TOU rates," *World Electr. Veh. J.*,

vol. 8, no. 2, pp. 521–530, 2016.

[7] C. Li *et al.*, “A new stepwise power tariff model and its application for residential consumers in regulated electricity markets,” *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 300–308, 2013.

[8] Q. Yan, I. Manickam, M. Kezunovic, and L. Xie, “A Multi-tiered Real-time Pricing Algorithm for Electric Vehicle Charging Stations,” *Ieee*, pp. 1–6, 2014.

[9] S. Mody and T. Steffen, “Optimal Charging of EVs in a Real Time Pricing Electricity Market,” 2012.

[10] M. C. Falvo and G. Graditi, “Electric Vehicles Integration in Demand Response Programs,” pp. 548–553, 2014.

[11] K. N. Kumar and K. J. Tseng, “Impact of demand response management on chargeability of electric vehicles,” *Energy*, vol. 111, pp. 190–196, 2016.

[12] F. Mwasilu, J. J. Justo, E. Kim, T. D. Do, and J. Jung, “Electric vehicles and smart grid interaction : A review on vehicle to grid and renewable energy sources integration,” *Renew. Sustain. Energy Rev.*, vol. 34, pp. 501–516, 2014.

[13] “FLEXICIENCY Project.” [Online]. Available: http://www.flexiciency-h2020.eu/.

[14] A. Andolšek, A. Zocchi, M. P. Nemček, A. Gómez, J. Bruna, and M. Á. Oliván, “Flexibility and optimization services validation in a microgrid,” in *CIRED Workshop*, 2018, no. 0444, pp. 7–8.

[15] A. Marinescu, C. Harris, I. Dusparic, S. Clarke, and V. Cahill, “Residential electrical demand forecasting in very small scale: An evaluation of forecasting methods,” *2013 2nd Int. Work. Softw. Eng. Challenges Smart Grid, SE4SG 2013 - Proc.*, pp. 25–32, 2013.

[16] “GAMS.” [Online]. Available: www.gams.com.

[17] R. De Coninck and L. Helsen, “Quantification of flexibility in buildings by cost curves - Methodology and application,” *Appl. Energy*, vol. 162, pp. 653–665, 2016.

Authors

	Gregorio Fernández: industrial engineer by the University of Zaragoza, specialized in electrical engineering, and a master degree in renewable energies by CIRCE Foundation. Works in CIRCE Foundation since 2010 in projects related to renewable energies integration, electric vehicle charge and grid impact and smart grids. Currently is working in its PhD in electric vehicle charging point optimization and grid impact reduction.
	Miguel Ángel Oliván: PhD in Physics (2016), MsC in Systems and Computer Science (2012) and Degree in Physics (1998). Twenty years of experience in software development focused mainly in data acquisition systems, device management, data analysis and SCADA systems. His main role in Fundación CIRCE is the design and development of Smart Grids SCADA systems and their integration with field devices, concentrators and remote or local managing algorithms. Additionally, his role includes the development of data management and data visualization software
	José Sediles: Engineer in computer science by Zaragoza University although took a year in luleå tekniska universitet (Erasmus Program). I have extensive experience as programmer analyst in several projects, and different technological environments. Currently I work as technical Researcher developing different software solutions.

	José Francisco Sanz: received the Ph.D. degree in electrical engineering from the University of Zaragoza. He is currently the Deputy Director with the IER Area of the Centre of Research for Energy Resources and Consumption (CIRCE), and a Lecturer with the Electrical Engineering Department, University of Zaragoza. His research interests are renewable energy integration, power electronic control for renewable energy sources, energy storage systems, grid connection systems and electrical vehicles.
	Juan Almajano: Master in systems computer science (Universidad de Zaragoza), Technical engineer in computer systems (Universidad Europea de Madrid). He works in the ICT CIRCE's department developing communication and control systems in micro networks. Realizes the integration and optimization of different generation, storage and consumption systems; achieving an optimization in energy consumption and network quality.
	Jorge Bruna works as Technological expert within Grid Studies and Smart grids Group in Grid and Substations Area. He received his B.Sc. degree in Industrial Engineering, specialising in Electrical Systems, from the University of Zaragoza (Spain) in 2008, his M.Sc. degree in Renewable Energies and Energy Efficiency with an Excellence Award and the PhD. Degree in Electrical engineering from the University of Zaragoza, in 2011 and 2016, respectively. Additionally, he authored several scientific papers in the field of Power Quality disturbances and also developed advanced measurements algorithms for monitoring complex Power Quality parameters. He is being involved in several EURAMET EMRP projects related to Power Quality, Electrical Metrology and Smart Grids as well as in several H2020 SmartCities-related projects.
	Andreas Muñoz: Telecommunications Engineer and Official Master in Control Systems, with more than 5 years of development and ICT integration experience in the electrical sector. He has carried out various implementations of local CAN and PLC communications for VE load control, as well as data modeling and standards analysis for the definition of the electrical system (H2020 Flexcoop project). Its most relevant ongoing reference is the coordination of the CIRCE ICT areas in the H2020 Flexiciency project, leading the technological prospecting of communication standards.