# Edge-Cloud based EMS for distributed ESS integration in Smart Grids

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***Abstract*—The ongoing energy transition is driving the transformation of the traditional centralized electric system into a decentralized one, integrating distributed energy resources along the grid. In this paper, a digital energy management strategy was developed for distributed energy storage systems integration in Smart Grids. This strategy was deployed in an Edge-Cloud architecture and validated in a test bench for a self-consumption case study. The proposed work obtained 41.5% savings on the electricity bill, a self-consumption level of 100% and a self-sufficiency level of 30.07%. The decentralized and digitalized control of a distributed energy resource was successfully validated, allowing the optimal integration of distributed energy resources and fostering their participation in grid services. The aggregation of these distributed resources can provide the increasing distribution grid flexibility requirements, thanks to the scalability and interoperability characteristics of the presented architecture. Opening the participation into new flexibility energy markets and the path to a more resilient and reliable grid.**

***Index Terms*— Cloud Computing, Digital Systems, Edge Computing, Energy Management Systems, Energy Storage Systems.**

## I. INTRODUCTION

Smart grids are crucial for improving energy security in the current energy transition, facilitating the creation of more intelligent and resilient grids. They also aggregate and manage distributed energy resources (DERs). The digital transformation of power systems is necessary to integrate the increasing number of renewable energy resources (RERs) efficiently [1], [2]. The Spanish Energy and Climate National Plan [3] has identified digitalization as a priority for the reduction of 23% of the greenhouse effect gases respect 1990, where 74% of the energy generation must be renewable. Higher renewable integration means transmission and distribution lines need to be more digitalized monitoring, control and automatization solutions. The energy generation will be distributed, intermittent and the grid energy flow bidirectional. This digitalization also brings advantages towards demand management and provides monitoring data from behind-the-meter (BTM) installations, resulting in an improvement of the communication and operation between the grid and the participants [4], [5].

Internet-of-Things (IoT) based platforms are being proposed as the solution to digitalization. The convergence of Edge computing and Cloud computing in smart grids plays a pivotal role in fostering an integrated energy and information infrastructure. By harnessing the power of Edge computing at the BTM level of the network, real-time data processing, automatization and analysis become feasible. In addition, Cloud computing provides solutions to high data rates with high computational and storage features. This integration facilitates the development of advanced smart energy management solutions, optimizing resource allocation and enhancing grid efficiency. Moreover, the coupling of Edge computing with Cloud resources extends the capabilities of traditional energy management systems, enabling participation in the emerging energy market via digital platforms and new business models [6], [7], [8].

Smart grids need to balance energy between generation and consumption while providing economical, reliable and robust operation objectives. This is obtained by energy management strategy (EMS) for DERs such as RERs, ESS, and plug-in EVs, among others. Different control frameworks exist with EMS for Smart Grids: a) centralized, b) decentralized and c) hierarchical. Centralized approaches provide optimal global performance, but a central controller failure directly impacts all DERs operation. A decentralized framework is a distributed structure where all DERs are managed independently, preventing the abovementioned failure. Finally, a hierarchical approach divides management into different stages, with a centralized control level and a distributed one. In this way, optimal control is obtained while ensuring the independent control of each asset [9].

The future decentralized and digitalized energy system [4], must be capable of managing different DERs deployed in the distribution network, see Figure 1. In this scenario, individual control and monitoring of each DER is of vital importance. The presented IoT-based EMS address these resources' current lack

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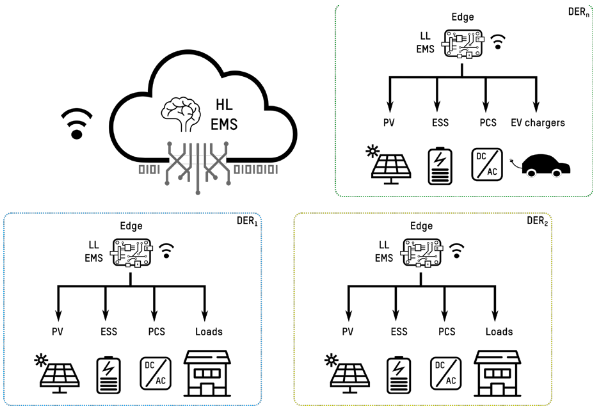


Figure 1. Roadmap to a decentralized future.

of visibility and interoperability. In addition, they allow the development of hierarchical EMS, managing DERs collectively across different locations.

Consequently, this paper presents an Edge-Cloud based EMS for distributed energy storage systems (ESS) integration in Smart Grids. The presented EMS (based on [5]) was migrated to a microservice-based Edge-Cloud architecture. This EMS comprises four modules and is oriented to the optimal battery control from a self-consumption installation. The data acquisition module, forecast module and the high-level EMS were deployed on the Cloud, while the low-level EMS was implemented on an Edge device responsible for controlling the test bench. Additionally, a web dashboard was developed for the visualization and monitorization of the digital platform.

This paper is structured as follows: Section III the integration of the distributed ESS is presented by explaining the digital EMS and the proposed Edge-Cloud architecture. Afterward, the studied case study and the developed test bench for the experimental validation is introduced. Consequently, in Section IV the obtained experimental results and the related discussion are shown. The paper finishes summarizing the main conclusions in Section V.

## II. DISTRIBUTED ESS INTEGRATION

The massive growth of DERs has a direct impact on the grid. The traditional grid infrastructure is not prepared to handle the high penetration of RERs, leading to various grid challenges. ESS play a crucial role in the integration of RERs due to their ability to mitigate the associated uncertainties. This is exemplified by the fact that, in Germany, 40% of recent self-consumption installations with solar photovoltaics were integrated with BTM batteries [10]. Furthermore, the existing distribution network is designed and operated in a centralized way, lacking the ability to effectively control the power flows from DERs due to insufficient information.

The development of digital tools and technologies is essential for addressing the integration and management of DERs. By incorporating smart meters, IoT devices, and edge computing, DERs can gain visibility and enhance their controllability for system operators. These digital solutions enable better monitoring, connectivity, and management of DERs, providing valuable insights and control over their power generation and consumption patterns.

In this section, the integration of the distributed BTM ESS of a self-consumption installation is explained. Aligned with the ongoing digitalization of the energy system, the developed digital EMS is presented. Subsequently, the designed and developed Edge-Cloud architecture is detailed along with its deployment.

### *A. Digital Energy Management Strategy*

The EMSs are techniques developed for the efficient and integrated management of all energy resources within a system. They are designed to achieve specific objectives and, therefore, require comprehensive information about energy system resources. Computational technologies such as cloud computing and IoT integration are increasingly being applied to energy generation and consumption, aiming to connect devices and improve operational visibility. The utilization of data and information is essential for decision-making. However, it should be noted that integrating digital technologies with EMSs presents challenges related to security, interoperation, and connectivity. Despite these challenges, the efficient and optimal digital EMSs offer opportunities and benefits that drive the evolutionary trend of these new technologies within Cloud-based environments [11], [12].

Cloud-based environments in the energy sector add value to end users by providing them with dynamic management capabilities for their energy assets. End-users can benefit from monitoring and controlling their assets, such as generation, consumption, and storage, through the use of sensors, smart meters, IoT, Cloud computing, big data, and other technologies. These environments are typically designed to maximize self-consumption levels and provide energy and economic savings. To achieve this, specific hardware and software architectures are required to integrate physical energy and data infrastructure [12].

Given the current needs, the development of the EMS was focused on deployment within a digital environment. The objective of the digital EMS for the integration of ESS was to maximize the self-consumption level. Additionally, boosts the self-sufficiency level of the installation, allowing end-users to become more independent from the grid. The digital EMS (an hierarchical approach) was composed of four different modules: a) data acquisition, b) forecast module, c) high-level EMS and d) low-level EMS. Each module was located in different environments, the first three modules were located in

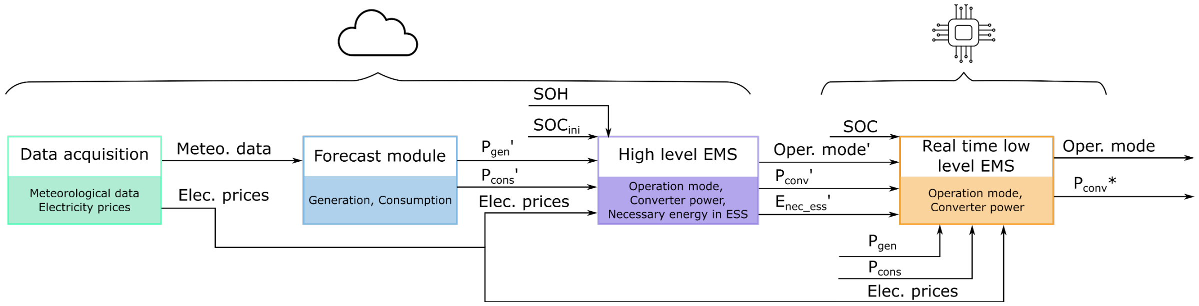


Figure 2. Digital EMS main diagram.

the Cloud, more precisely, in the AWS Cloud, and the last one was in the edge device, see Figure 2.

The data acquisition module is responsible for collecting all the necessary data for the operation of the EMS. In the first place, meteorological data is recollected for the forecast module from the Basque Meteorological Agency database [13]. In second place, Spanish electricity prices are obtained from the application programming interface (API) of the Spanish system operator (REE) [14]. The forecast module generates predictions of the photovoltaic installation generation and a tertiary building consumption. The machine learning method utilized was the regression tree technique, as it is widely used for trend analysis [15], [16]. The high-level strategy is a rule-based approach that determines the battery operation, aiming to minimize grid consumption during periods of high electricity prices. This is obtained by calculating the required energy stored in the battery to achieve maximum reduction in grid consumption.

These three modules were integrated and developed in the Cloud because they are executed once daily and require heavy datasets. Thereby enabling the automation of training and retraining processes for more intricate and extensive prediction models.

The last module, the low-level strategy, was designed using a rule-based method that was aligned with the previous one's purposes. The main task consists of correcting the battery operation considering the required energy in the battery, electricity prices and the instantaneous measurements of the generation, consumption, and battery status. It has been incorporated into the edge device as it needs to be executed in real-time and requires instantaneous measurements. Moreover, in cases of communication failures between the Cloud and the edge (e.g., internet network downtime, server unavailability), the edge device can operate autonomously.

### B. *Edge-Cloud Architecture*

Edge-Cloud Architecture + dashboard web

## III. CASE STUDY

The case study intends to validate the decentralized control of an ESS integrated into a Smart Grid. For this purpose, a behind-the-meter ESS located in a self-consumption installation with the proposed digital EMS was studied. The ESS is located in Hernani (Spain), in the energy laboratory of IKERLAN. The aim of the ESS is to increase the self-consumption and self-sufficiency levels. The self-consumption installation is composed by a photovoltaic installation located in the roof of the building. The consumption is emulated considering a tertiary building. That is why it is assumed that the installation has contracted a 2.0TD tariff (Spanish domestic electricity tariff in 2022, BOE-A-2021-21208). Finally, the integrated ESS has a lithium-ion chemistry.

### A. *Test bench*

The previously mentioned case study was experimentally validated in a test bench where a distributed ESS was integrated with an Edge-Cloud based architecture, see Figure 2. This test bench is composed by hardware and software parts. The hardware is consisted of: a) a LFP battery of 180 Ah, 48 V and 8.64 kWh characteristics, b) three DC/AC power converters pf 8 kW, c) 20 photovoltaic panels, being 4.8 kW of installed power and d) Variscite IMX8 Mini. This edge device has connectors for CAN and Modbus TCP/IP communication protocols to monitor the battery and control the converters, respectively, and wi-fi for the communication with the AWS Cloud. In addition, the dashboard web is displayed in a Human-Machine Interface (HMI). The edge device emulated the consumption monitorization, considering a contracted power of the installation of 5 kW. The software of the proposed digital EMS was fully developed in the programming language python.

## IV. EXPERIMENTAL RESULTS

The proposed integration of an ESS with a digital EMS developed within an edge-cloud architecture was validated with the presented scenario in the test bench, see Section III. The

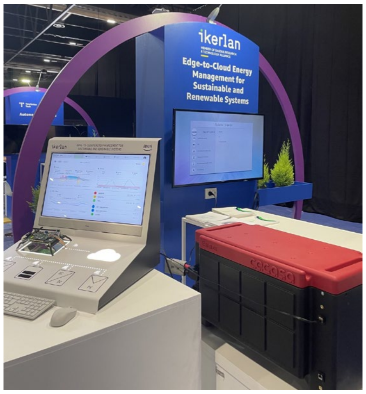
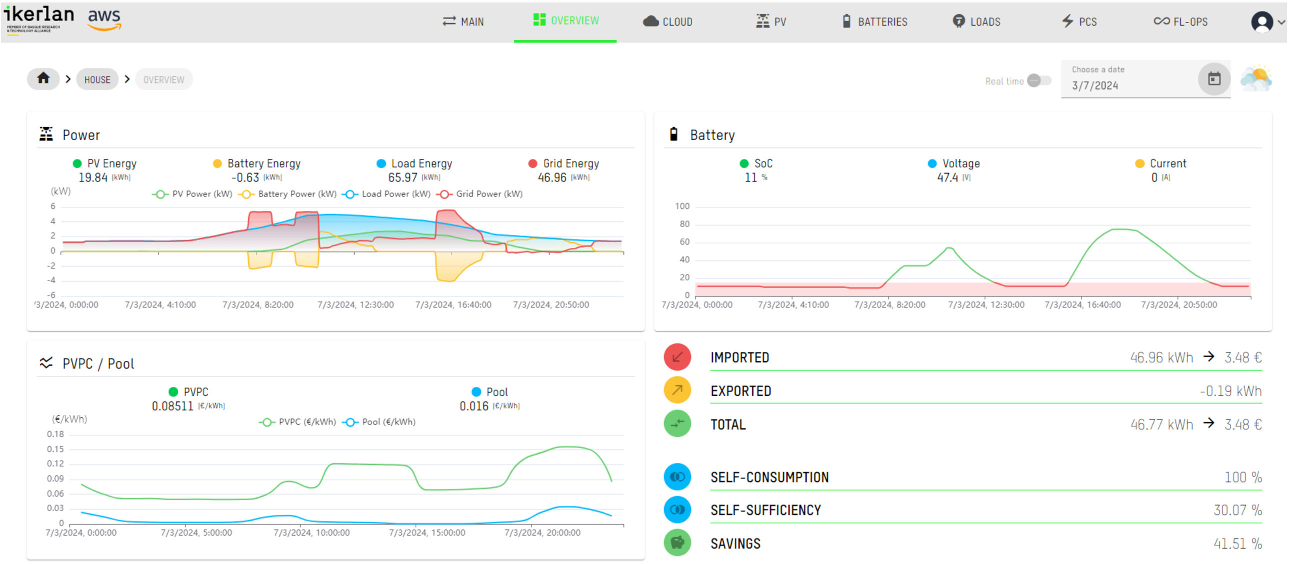


Figure 3. Distributed ESS test bench.



Choose a date
3/7/2024

PV Energy 19.84 (kWh)
Battery Energy -0.63 (kWh)
Load Energy 65.97 (kWh)
Grid Energy 46.96 (kWh)

SoC 11 %
Voltage 47.4 (V)
Current 0 (A)

PVPC 0.08511 (€/kWh)
Pool 0.016 (€/kWh)

| | |
|---|---|
| IMPORTED | 46.96 kWh → 3.48 € |
| EXPORTED | -0.19 kWh |
| TOTAL | 46.77 kWh → 3.48 € |
| SELF-CONSUMPTION | 100 % |
| SELF-SUFFICIENCY | 30.07 % |
| SAVINGS | 41.51 % |

Figure 4. Dashboard web platform on 07/03/2024.

correct operation was validated through the main page of the dashboard web interface. This main dashboard page displays all assets power flows, battery status (including state of charge (SOC), voltage and current), electricity prices, and daily economic and energetic balances, along with key indicators.

Figure 4 shows the operation of the test bench on the 7th of March 2024. In the chart labelled as power are depicted in green the generated power by the photovoltaic installation, in yellow the battery power, in blue the consumption power and in red the utility grid power balance. On the other hand, the graph labelled battery graphs the SOC profile with the battery voltage and current. Above the first graph, the electricity prices are plotted, with the green line the PVPC (the cost for consuming from the grid) and the blue one the pool (the revenue for exporting the power surpluses). The energetic/economic and key indicator results are divided in the last part of the page above the battery graph.

Firstly, it must be mentioned that the generation did not exceed the consumption, being a day without surpluses. The day starts with the battery discharged (minimum SOC of 10%), and as the electricity price is low, the consumption is supplied from the grid. Afterwards, the operation mode is not changed to charge until the low-level strategy received the required energy stored in battery command at 8:00 (3 hours before the high prices period, in this case, 11:00). At 9:00 the charge is stopped due to an increase in the electricity price and because the strategy foresees that the next hour the prices are lower, prioritizing charging the battery in that period. Consequently, the charge is stopped at 11:00 as starts the period of higher prices, here the consumption is supplied by the generation, the battery and the grid.

The battery is discharged until the minimum SOC, which occurs at 13:20, being the consumption supplied from the grid. This is maintained until again the low-level strategy received the required energy stored in battery command at 16:00. In this period of battery changing the electricity prices are low, and the battery changed to stand-by mode at 18:00 due to the increase of the prices. At 19:00 the battery changed to discharge mode due to the period of highest electricity prices of the day and all the consumption is supplied by the battery. The discharge is carried out until the battery arrives to the minimum SOC. It can be seen how the battery avoids consuming from the grid in the highest price period. This results in grid consumption when prices are low or near their mean value.

Analyzing the overall energetic and economic balance of the day, the energy imported from the grid was 46.96 kWh, resulting in an energy cost of the electricity bill of 3.48 €. Thanks to the self-consumption installation (photovoltaic generation and ESS), savings of 41.51% were achieved. Furthermore, the obtained self-consumption level was 100%, indicating that all the generated energy was consumed. In terms of end-user self-sufficiency, a level of 30.07% was attained for that specific day, resulting in an increase in the end-user grid independency. Additionally, an annual analysis was conducted to determine the average bill reduction. The simulated year was 2021, and an electricity bill reduction of 22.84% was obtained.

## V. CONCLUSIONS AND FUTURE LINES

This work designed and developed an Edge-Cloud based EMS for an ESS integration in Smart Grids, more precisely in a self-consumption installation. The presented Edge-Cloud architecture was successfully integrated into the test bench, validating the decentralized and digitalized control of the ESS. In this validation, 41.51% of savings in the electricity bill's energy cost were achieved with 100% and 30.07% of self-consumption and self-sufficiency levels, respectively.

The growing number of DERs across the distribution network and the emergence of advanced architectures for their integration and aggregation, such as energy communities, will request several management layers capable of handling increasingly complex decisions. The aggregation of DERs enables a greater amount of participation opportunities in services, as it allows for reaching the required minimum bid sizes. This complexity arises from the need to consider multiple service participation, thus requiring the EMS to adapt its objectives, respond to different goals, set preferences, and prioritize objectives accordingly. Moreover, managing a larger number of resources and distinguishing between them will entail accounting for the behaviour of different DERs, thereby adding further intricacy to the EMS.

Cloud-based EMSs offer enhanced computing capabilities, enabling the development of sophisticated strategy algorithms based on extensive historical data, data processing, machine learning, and optimization techniques. Apart from that, the connectivity with a large amount of DERs situated in diverse locations enables higher levels of management and control, expanding the range of grid energy and power service offerings.

It has been observed that IoT-based solutions at the unit scale exhibit scalability and the ability to replicate installations and facilities, thereby aggregating them within the same Cloud. This facilitates the monitoring and control of DERs from the household level to the energy community, smart grid, or network level. Considering that energy trade involves monetary transactions between various parties, there is an increased interest from external actors, necessitating the assurance of cybersecurity measures.

In the future, digital tools must be developed to foster open participation in the energy market, ensuring non-discriminatory access to DERs. It is evident that there is a growing necessity for flexibility services in transmission and distribution networks, which will lead to the development of new energy markets. The digital EMSs that enable decentralized control and monitoring of DERs will play an important role in offering flexibility, benefiting end-users both energetically and economically and the electrical system by enhancing reliability and resilience, reducing the impact of power outages and ensuring uninterrupted and quality power supply to end-users.

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