Methodology for the sizing of a hybrid energy storage system in low voltage distribution grids

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***Abstract*—This paper presents a methodology for the sizing of hybrid storage solutions in low-voltage distribution networks. A hybrid storage solution is defined as that able to integrate and maximize the performance of a heterogeneous grouping of battery types. The methodology relays on a step-by-step analysis of field data collected from the area at which the hybrid solution is intended to be connected to. It also considers diverse restrictions related to available budget, technical constraints related to the different technologies included, and business and future exploitation aspects. A study case based on a real demonstration is presented to validate the proposed methodology.**

***Keywords*—Power electronics, distribution grids, hybrid storage systems, sizing.**

I. INTRODUCTION

Energy storage systems are progressively gaining momentum in diverse strategic fields such as the electromobility, renewable-based generation systems and power networks [1]. There is a technical trade off in the design of storage solutions based on batteries: they can provide peak power during a short time, or alternatively, a sustained but reduced power output during long periods of time. The solution most adopted in renewable energy installations, where the electrical network is not sufficiently robust and reliable, is to cover requirements of storage capacity with cheaper technologies such as lead-acid, while power requirements are covered with lithium-ion. This vision yields hybrid storage solutions [2]. With the proper management of each of the batteries composing such storage system, it is possible to maximize the performance of it, accounting on a reduced investment with respect to state-of-the-art solutions based on just one battery technology.

Adopting such idea, the focus of the paper is propose a methodology for the sizing of a hybrid storage solution based on lead-acid and lithium-ion batteries. The aim of such device will be to maximize the integration of local renewable generation in a neighborhood with voltage variability connected to the main distribution grid, and dominated by domestic consumers with PV. The storage solution maximizes the security of supply for customers in case of mains failures, while in grid connected mode, the focus is on the management of energy through the neighborhood according to the specificities of different defined use cases.

The paper's frame is the European Union's energy challenges. The project, which is named Resolvd, aims to make a valuable contribution by increasing energy efficiency and utilizing renewable Distributed Energy Resources (DER) in the Low Voltage (LV) grid, while maintaining or improving the quality of supply. By employing ICT infrastructure, power electronic and hybrid energy system devices and a custom management intelligence.

According to Resolvd definition, the hybrid storage system deals with: (i) a reduction of congestion and investment on the LV grid by managing power flow and allowing load balancing between phases, (ii) a increment of voltage stability maintaining the voltage level along the network, and (iii) a reduction of demanded current and peak shaving at the substation level is expected [3].

In the literature, there are various battery sizing examples such as: [4], [5] which define an energy storage system methodology for a microgrid using modeling language for mathematical programming and [6], [7] propose a problem that minimizes the investment cost of the energy storage system and the operating cost of a microgrid with intermittent of renewable generation. Therefore, the main objective of this paper is to present the methodology for sizing hybrid energy storage systems for low voltage distribution grids.

The structure of this paper is as follows: firstly, in Section II is briefly introduced use cases which request the hybrid storage solution, the pilot site where the power electronic device and hybrid storage solution can be deployed and finally are lightly enumerated some energy storage restrictions. Following, Section III presents the methodology; Section IV introduces the case study, and, finally, Section V enumerates the conclusions.

II. PREREQUISITES

Above mentioned, a main goal of Resolvd project is to improve the efficiency and hosting capacity of distribution networks. To do so, it is developed an innovative advanced power electronics device, with integrated an hybrid storage energy system will provide both switching and energy balancing capacities to operate the grid optimally [8]. It controls continuously the power flow between the hybrid storage system and the grid, and also between grid phases, will result in a flatter and reduced demand curve at the substation level with an associated loss reduction and an improved voltage control and quality of supply [3], [9], [10].

The decision on how to size the ratings of a hybrid energy storage solution and its associated power electronics device is unavoidably affected by the constraints suggested by the Use Cases (UCs) under study in the project (see a list of UCs in Subsection II-A), a description of the pilot site (see it in Subsection II-B) and the constraints for energy storage technologies (see them in Subsection II-C).

A. Applications of the hybrid storage solutions

In this subsection a list of the seven involved UCs is introduced where the hybrid energy storage system and its associated Power Electronic Device (PED) take part in.

- UC01: Prevention on congestion and over/under voltage issues through local storage utilization and grid reconfiguration. In others words, the solution would exchange power during few hours (e.g. peak consumption hours) continuously with the grid for line congestion mitigation.
- UC02: Voltage control through local reactive power injection [11]. In this UC, the Power Electronic Device (PED) that integrates hybrid storage solution might be required to exchange reactive power with the grid. This means that no battery is needed in this case.
- UC03: Improving power quality and reducing losses through power electronics. As previous UC, the power electronic device will compensate current harmonics and phase unbalances at its point of connection. As for the UC02, no battery is needed to do so.
- UC04: Local storage utilization to reduce power losses. The idea is to manage energy storages optimally so as to reduce power flows within the grid, this way reducing involved distribution power losses.
- UC05: Self-healing after a fault. The PED and storage solution would be required to act following an exogenous command to ensure the continuity of supply to customers nearby.
- UC06: Power management in intentional and controlled-island mode.
- UC07: Detection and interruption of unintentional uncontrolled island mode. In this UC the PED would be required to eventually exchange power with the grid just during a short time.

To sum up, some UCs comprise mainly the usage of device in terms of power while others energy exchanged with the main grid. The most stringent in terms of power UCs are the UC02, UC03 and UC06. Use cases UC02 and UC03 require for the PED to exchange active and reactive power with the main grid (no battery is needed to do so). Conversely, for UC01 and UC06, batteries are required to be charged and discharged during diverse hours to supply the customers nearby while in isolated mode, so this is considered as the most demanding UC in terms of energy storage. Finally, the requirements derived from the UC05 and UC07 are considered less stringent than other UCs.

B. The pilot site

In this subsection the pilot site is described where the innovate solution will be deployed and evaluated. The selected network belongs to EyPESA. EyPESA is a Distribution System Operator (DSO) that operates a distribution system in Catalonia (Spain). Measures aiming at the reduction of losses and resolve incidences will be implemented and tested in a EyPESA's LV system depicted in Figure 1. This pilot is a rural area at the north of Catalonia. The pilot site in EyPESA's grid concerns a rural area in which the majority of consumers are residential ones. This area concerns two radial lines from two Secondary Substations (SS) (marked in purple in Figure 1). The exact location of the pilot is in the town of L'Esquirol located in the Osona region in Catalonia (Spain). This town is considered a concentrated rural area with 2141 inhabitants [12].

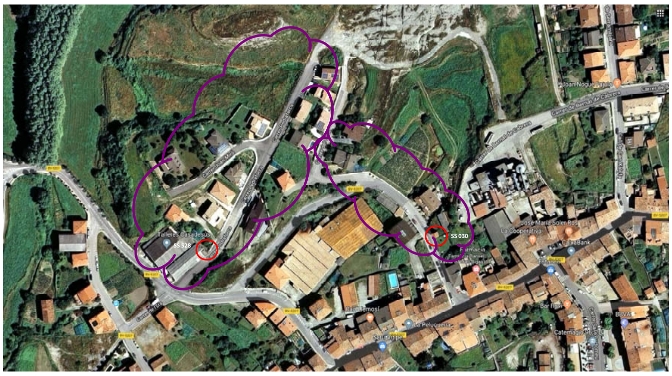

Fig. 1. Pilot site

Domestic consumers are connected along these two radial systems (from the named SS 030 and SS 528). Every consumer presents a power demand lower than 10 kW peak. Some of these consumers are equipped with distributed generation (PV). In the short term, during project execution period, a new line will interconnect the these two radial networks.

By the way of example, Figures 2 and 3 present the real consumption patterns (the active and reactive power generation adopts positive values) from these two radial system (at SS 030 and SS 528) covering around 4 days from August 2018. It is observed, on the one hand that there are peaks of generation in the midday in both SSs, especially in SS 528. In addition to these measurements, the registers from Smart Meter (see Figure 4) are also considered in order to test the proposed methodology.

C. Energy storage restrictions

Finally, to conclude, in this subsection energy storage restrictions for the sizing of the hybrid storage solutions are presented in Table I. They refer to available budget, technical characteristics and future business exploitation of the device.

III. METHODOLOGY

In this section the methodology is presented, it provides a systemic and comprehensive way the energy and power

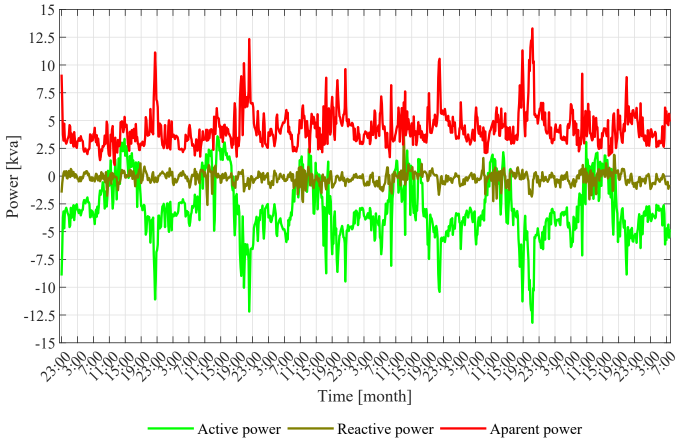

Fig. 2. SS 030 consumption patterns (pilot LV line)

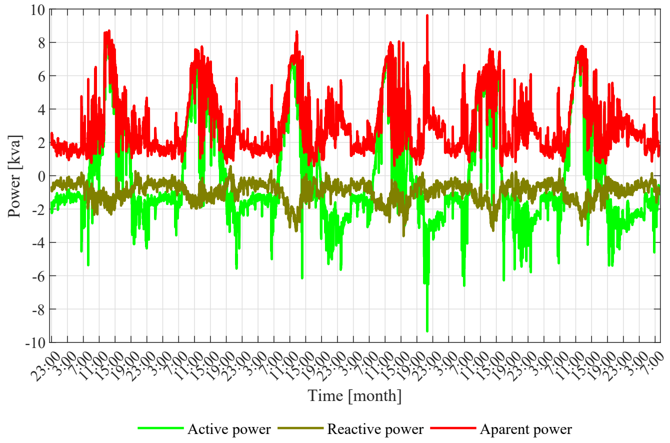

Fig. 3. SS 528 consumption patterns (pilot LV line)

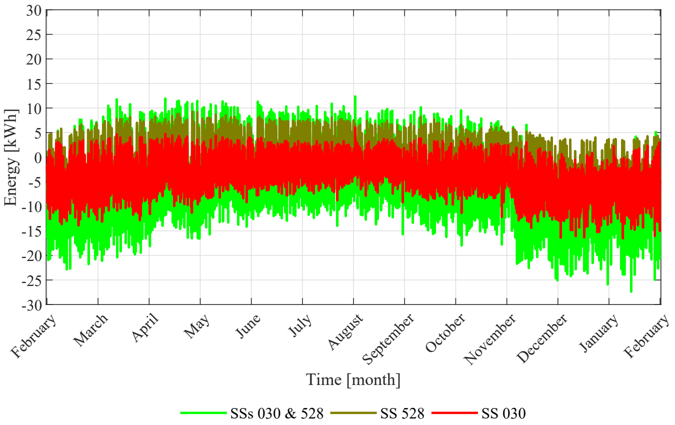

Fig. 4. Pilot Smart Meter annual registers

TABLE I. ENERGY STORAGE TECHNOLOGIES REQUIREMENTS

Restriction	Description
Available budget	Budget for hybrid storage solution: Available budget should include all power electronics, cabinets, protections, human machine interface; as well as all energy storage technologies.
Technical characteristics	Power and energy requirements that should be determined according to the use cases or services to be provided.
Technical characteristics	Cyclability and time response: According to the type of services to be provided, it is important to include technologies with large cyclability, short time response and high power rates; and at the same time include others able to provide a sustained power during several hours with relaxed requirements on response time. This permit to effectively perform services related to power quality (e.g. to smooth out fast power fluctuations in grids) and others related to the security of supply to customers and renewables integration in an hourly basis.
Business	In electromobility lithium-ion types are vastly utilized. A large number of second life batteries will be in the market in the coming years, so it has sense to adapt the design of the hybrid solution so as to be able to integrate second life batteries from electric vehicles. This means to take into account usual voltage levels for such batteries (around 200 - 400 Vdc). For instance, the rated voltage for the Nissan Leaf battery pack (24 kWh version) is 360 Vdc.
Business	It may be interesting to include a dc output for a battery pack rated at relatively low voltage, e.g. around and/or less than 200 Vdc. This would permit to integrate low cost packs, such as lead-acid ones. The rated voltage of such packs would be low due to the reduced cell voltage (e.g. 2.0 Vdc for lead-acid).
Business	It may be interesting to include energy storages (and also their related dc-dc power electronic modules) rated at different voltages. This provides the hybrid solution with flexibility and business exploitation potential.

requirements for the hybrid solution as a whole, as well as the sizing for each of the batteries included in there.

It is performed by a central actor which can be named as the Grid Planner (GP). The GP is responsible of carrying out the analysis for commissioning the a hybrid storage solution. Moreover, the GP triggers a process for locating and sizing a storage solution to solve future problems in a specific part of the LV distribution system. To do so, different inputs are required from a group of human actors from the DSO staff and/or from the technology providing company, that collaborate to identify the most suitable layout of the Power Electronic Device (PED) deployment. This group of people can be identified as the Planning Task Force (PTF).

The dimensioning and location of the hybrid storage solution is divided into four steps: the first step of the methodology refer to the grid information and data collection, the second step is to identify current and future grid issues, the third step is to propose a collection of possible solutions and final step is to chose the best one.

Therefore, above mentioned, the GP is who starts and asks the PTF about specific information from the DSO. So, upon GP request the first step is performed by the PTF collecting the following information (see also Figure 5):

- Financial information – budget, cost associated with the grid update, cost associated with technical/non-technical losses, cost associated with each grid issue, prioritization of problems, cost and physical constraints of technology
- Parameters that allow drawing future scenarios of energy generation/consumption in the grid (e.g. DER penetration increase).
- Grid characteristics – physical and geographical constraints, grid map, grid asset characteristics, and grid physical limits, obtained from the Geographic Information System.
- Historical data of consumption/generation are extracted from the data base of the Meter Data Management System.
- Power data measured through power quality analysers: if the legacy system does not include these devices, some portable items can be installed for a certain period.

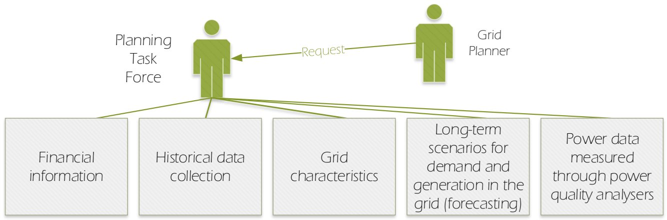

Fig. 5. Planning Task Force actions

Once all the required information has been collected by the PTF and provided to the GP, the second step starts. In particular, the GP taking into consideration the previous outputs performs an analysis for identifying technical problems in the grid in present and future conditions of consumption and generation in two parallel ways:

- The data collected by the analysers, is processed focusing on the presence of harmonics, phase unbalances, presence of reactive power, voltage variations and current congestions, identifying the most serious current technical problems and the affected elements.
- Foreseeing a possible increase/decrease in DER penetration or loads, the future generation and consumption patterns are forecasted permitting to identify the potential future technical problems.

Following, the GP starts the third step and identifies a list of candidate installation configurations - scenarios. They are selected according to under/over voltages, congestions, current power quality and among other issues and technical constraints. The list of candidates must be defined in terms of the minimum power and energy, physical space, geographical location and available budget requirements.

To conclude, for each of the candidate solutions, the GP calculates and simulates what would be the statistical positive impact on the grid operation, both for the present and for the future conditions. The latter consists in the percentage of cases in which a certain technical problem or critical situation would be solved. The events taken in considerations are over/under voltages, reactive power, phase unbalance, congestions, harmonics and operation in island mode. Other parameters, such as cost of the installation, return of investment, compliance with DSO's priorities and interests are also considered to chose the most suitable solution.

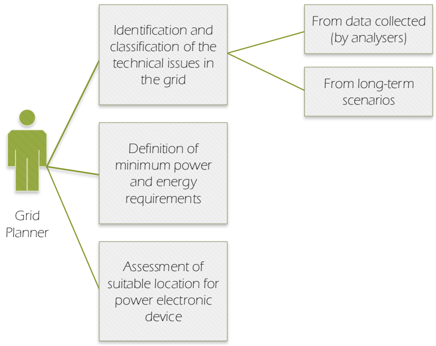

Fig. 6. Grid Planner actions

IV. CASE STUDY AND RESULTS

This exercise is carried out to chose a good solution in order to maximize the integration of local renewable generation in the pilot grid (see topology in Figure 7). Above mentioned it is dominated by domestic consumers with PV. In addition, in the short term, during project execution period, a new line will interconnect the two radial networks as depicted in the figure (blue dashed line), thus improving the reliability and security of supply to customers.

This new line, along with the energy storage capability provided, in fact, will permit to eventually build up an island concerning all consumers marked (black triangles) in case of severe failures from distribution system and secondary substations. Such scenario will be one of interest for the objectives of the project while considering the PED connected to the grid. In addition, the new line enables new operation options, not only in island mode, allowing to move domestic consumers from a substation which experimented an electrical issues to the other. When not in island mode, focus is on the management of the energy through the microgrid constituted by the domestic consumers according to the specificities of different use cases and the particular grid operation option.

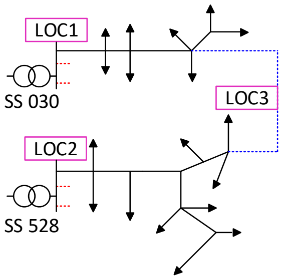

Fig. 7. Pilot network topology

A. *Location definition*

There are three main possible locations for connecting the PED in the pilot site. In Figure 7, these are noted as LOC1, LOC2 and LOC3. LOC1 and LOC2 correspond to the SS 528 and SS 030 respectively. LOC3 is placed across the above mentioned new line interconnecting the two radial branches.

In general terms, to install the PED in a secondary substation is preferable than doing it throughout the LV network. It helps to maximize the effectiveness while exchanging reactive power, compensating harmonics and power unbalances among the three phase distribution system, while to install the PED in the end of line helps to support the voltage stability or to energize an island.

The most interesting secondary substation for PED location is SS 528 because of the following reasons: i) the loading of the transformer at SS 528 is greater than in SS 030 (148 kW of peak demand at a transformer rated at 250 kVA versus 132 kW at a transformer rated at 630 kVA); ii) the heterogeneity of consumers is higher in SS 528 than for SS 030; iii) the overvoltage at the SS 528 is reaching critical values and there is need to compensate these over-voltages. Figures 8 and 9 depict the whole consumption (including the other lines) of SS 030 and SS 528 in order to illustrate the previous points.

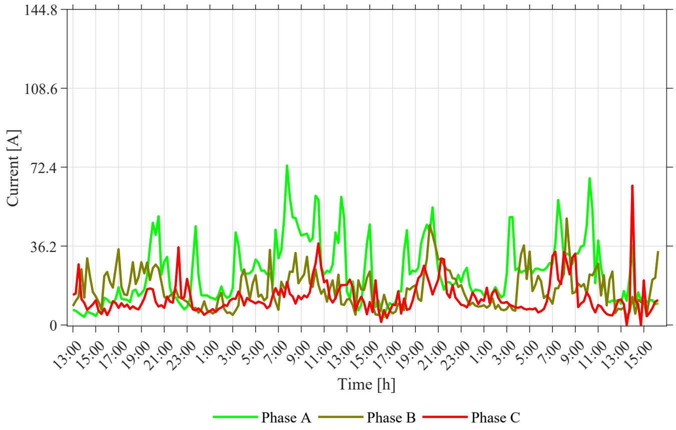

Fig. 8. Currents at SS 030

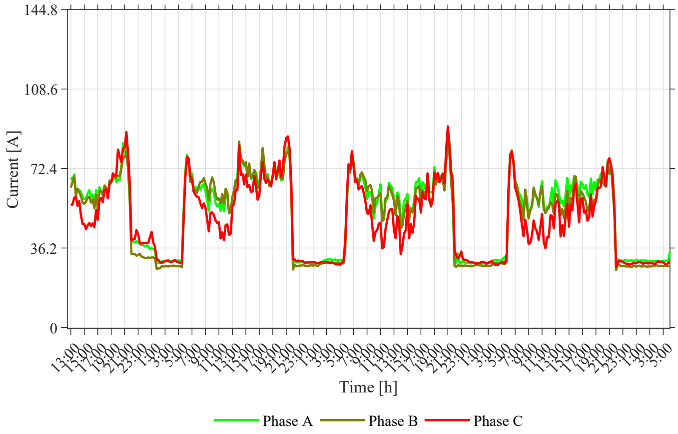

Fig. 9. Currents at SS 528

However, a conclusion is that the requirements in terms of power to solve power quality issues and while operated in islanded mode are similar according to the two probabilistic analyses (see Figures 10 and 11). They focus on the radial systems connected at SS 030 and SS 528 dominated by domestic consumers and quantify the magnitude of the current to be exchanged by the power converter to provide the services of power balancing, reactive power compensation, current harmonics mitigation (UC03), and feeding an isolated neighborhood (power management in intentional and controlled-island mode UC06).

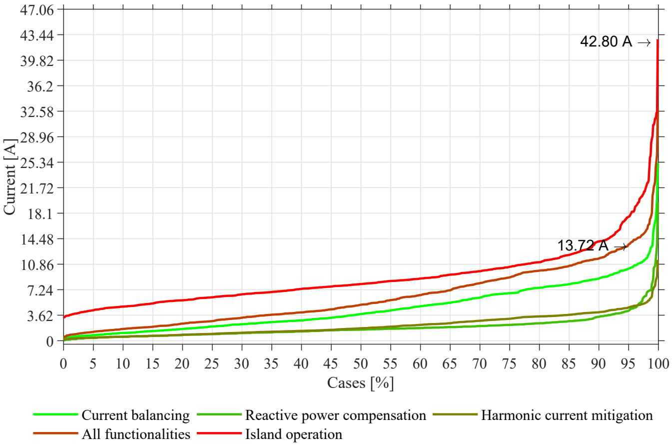

Fig. 10. Rated currents at radial system of SS 030

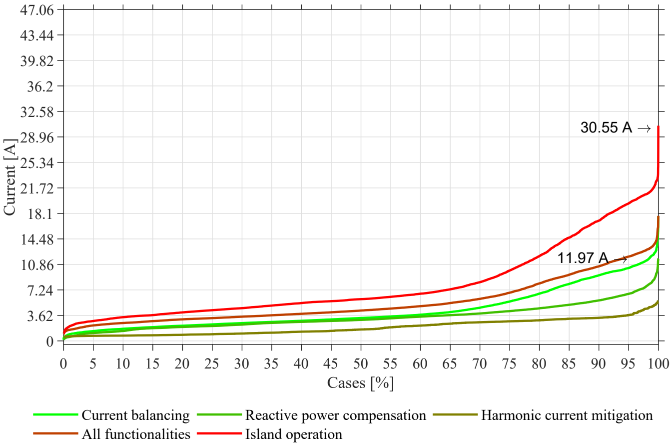

Fig. 11. Rated currents at radial system of SS 528

So technically both SS 030 and SS 528 are eligible and valid locations. Even, the eventual interconnection of the two systems may even ease the decision on the location of the PED, since it could be able to provide services to all consumers, regardless its association to one or another SSs.

Thus, for the final decision on the location of the PED, other constraints like the available space at each SS comes into play at this point. In particular, for the purposes of the present project, the connection of the PED to SS 030 is considered for the available space as preferable among eligible options.

B. Power sizing

In the following exercise, the PED is considered as a black box. The aim here is to determine the power requirements for the power electronic modules. As above mentioned, UC02, UC03 and UC06 are the more stringent in terms of exchanging active and reactive power with the main grid. In addition, note that UC02 (i.e. voltage support) and UC03 (i.e. power quality support) are complementary services which can be activated while UC01 and UC04 are performing (i.e. exchanging active power from batteries to the main grid for avoiding congestions and reducing losses, respectively).

On the one hand, as Figures 10 and 11 depicted that for 95% of the cases in SS 030 and SS 528, the PED would have to exchange around $I_{l_{SS030}}$=13.72 A and $I_{l_{SS528}}$=11.97 A per phase at most for providing all three above mentioned services simultaneously. As previously mentioned, the two radial lines fed by SS 030 and SS 528 respectively may be eventually interconnected, so it makes sense to calculate the ratings of the PED to provide power quality services to the resulting compound neighborhood. So adding SS 528 to SS 030, it results that the required power for the front end power conversion system of the PED to provide power quality services is $I_l = 13.72$ A + 11.97 A. Thus, the power rating of inverter should be around at least S_N = 17.80 kVA. Since the power rating of one inverter module for the PED is around 25 kVA, it is clear that just one module would be enough to provide power quality services to the grid.

On the other hand, according to the most challenging situation (UC06), as Figures 10 and 11 depicted the maximum current peak measured in both analyses is 30.55 A and 42.80 A for SS 030 and SS 528, respectively. So adding SS 528 to SS 030, it results that the required power for the front end power conversion system of the PED to feed an isolated neighborhood is $I_l = 30.55$ A + 42.80 A. Thus, the power rating of inverter should be around at least S_N = 50.82 kVA.

Note that, as Figure 4 shows, the maximum hourly demand in summer does not exceed 15 kWh, reaching 25 kWh in winter. Conversely, self-generation is maximum in summer and, obviously, minimum in winter. Such stationarity in yearly profiles affects the required ratings for the PED while providing the necessary services.

To take into account the increment in the magnitude of power consumption in winter with respect to the data considered for sizing calculations in this document, the number of front-end inverters for the PED is incremented to 3, thus incrementing the power capacity of the device up to 75 kVA.

In regard to the sizing of the dc-dc modules integrating the different energy storages, their power rating is similar to that for the inverters for coherence. The number of dc-dc modules will depend on the number of battery packs to be integrated and this decision will be addressed in the following section.

C. Storage capacity estimation

The storage capacity estimation is performed according to the Smart Meter registers (see Figure 4). The result of the analysis is presented through a probabilistic storage capacity map. Figures 12 and 12 depict the energy to be exchanged by the hybrid solution according to the demand requirements of the neighborhood connected along the radial line attached to each of the secondary substations for SS 030 and SS 528, respectively. The vertical axis presents the battery storage capacity, the left-horizontal axis presents the number of hours at which the energy exchanged by the hybrid storage solution is enough to cover the demand of the corresponding secondary substation and the right-horizontal axis depicts the number of cases.

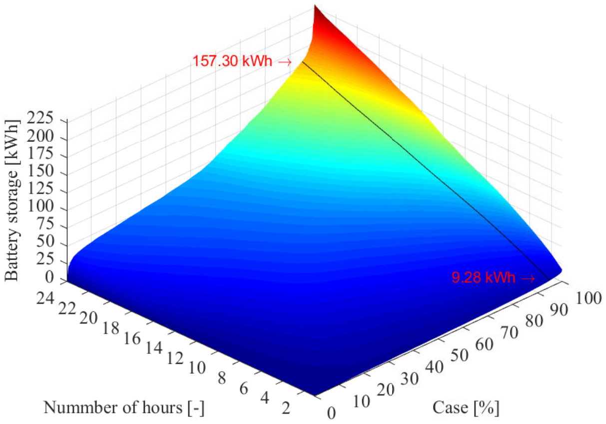

Fig. 12. Probabilistic storage map of SS 030

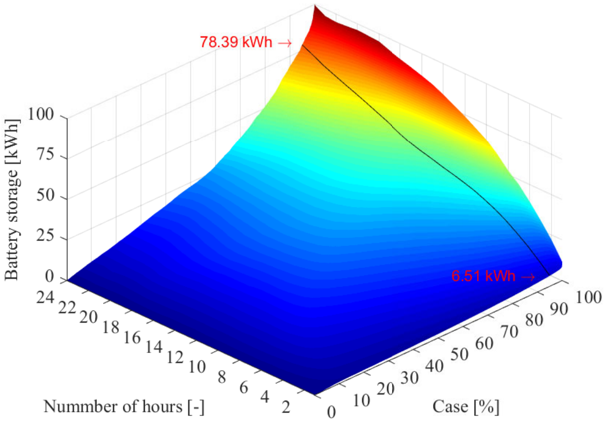

Fig. 13. Probabilistic storage map of SS 528

As it can be observed, SS 030 is more demanding in terms of the energy to be provided by the hybrid storage solution for security of supply for customers than SS 528. For SS 030, the PED should be rated between 9.28 kWh to 157.30 kWh to satisfy the demand of customers from one hour to a day for the 95% of the cases. While, for SS 528, the hybrid storage solution should be rated between 6.51 kWh to 78.39 kWh. Finally, Figure 14 depict the whole system demand for supplying all consumers attached to SS 030 and SS 528, energy requirements increase to 15.56 kWh and 284.60 kWh.

According to the requirements for the energy storage technologies, a market assessment has been carried out. As a result, four main types of electrical and electrochemical energy

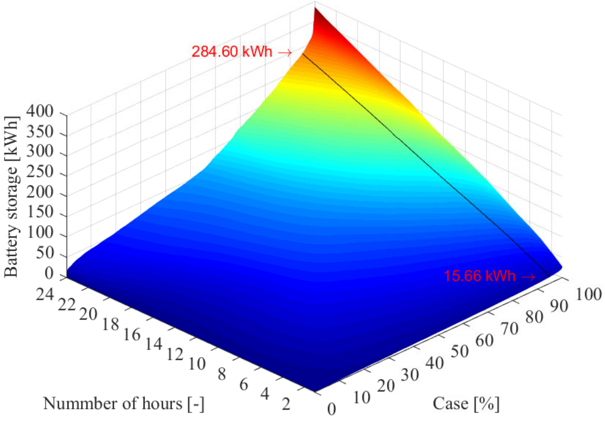

Fig. 14. Probabilistic storage map of whole system

storages are considered as suitable for the purposes of the project and commercially available in the market.

Different options on lead-acid, lithium-ion, flow batteries and supercapacitors have been considered so as to have flexibility in proposing design options in the following subsection. For these design options though, flow batteries are not to be considered, since available commercial offers are extremely high-priced for the purposes of the present project.

The selected option is a combination of two different battery packs, the first pack is a lead acid pack about 14 kWh and the second is a lithium-ion pack about 30.7 kWh. The whole solution has a 44.7 kWh of energy storage capacity. According to previous analysis, this is enough to supply the domestic customers connected at SS 030 for 5 hours while isolated from the main grid; to those at SS 528 for more than 10 hours; and to the whole neighborhood during 4 hours approximately. Each battery type will be connected to a dedicated dc-dc converter rated around 25 kVA, so adding both batteries the PED could exchange around 50 kW with the main grid for feeding an island. Thus fulfilling the requirements of the system in terms of power also under such situations.

Combining both electro-chemistries (lithium and lead) offers many advantages [13]: i) the response time of the lead-acid pack can be greater so the lithium-ion pack would react as fast as required when needed instead. This would permit to extend the lifespan of the lead-acid pack; ii) the space required for the hybrid storage solution is lower than in case of using just lead-acid packs. This is because the specific energy for lithium-ion batteries (so the ratio Wh/kg of the battery) is higher than for lead-acid batteries; iii) the average efficiency of the chemical – electrical power conversion of the PED is higher than in the case of using solely lead-acid packs; iv) the lifespan of lithium-ion packs is higher than for lead-acid ones, so this enhances the lifespan of the whole PED and total operating costs of the system.

The hybrid storage solution thus would include a dc-dc converter with a “storage port” rated at 240 V, and other rated at 370 V. Such variety provides the PED with flexibility answering to one of the technical requirements of the project.

V. CONCLUSIONS

This paper has presented the methodology performed for locating and sizing a hybrid storage solution in the frame of Resolvd project. The methodology has been adapted here to fit it into a manual step-by-step design process. This results into a comprehensive exercise that fits with a objective of the Resolvd project. The location and sizing of the PED, as an energy storage system, takes into account several aspects such as: i) the requirements of the use cases, ii) available budget, iii) performance of the eligible energy storage technologies, and iv) business exploitation potential of the solution.

The selected location for the PED into the EyPESA pilot network is the secondary substation coded as SS 030. In this location, the contribution of PED providing power quality is maximum. This refers to the demand for compensating reactive currents and harmonics, as well as balancing the loading conditions among the three phases of the system.

In regard of the required size for PED, this is determined around 75 kVA in power and 44.7 kWh in energy. It integrates a lead acid pack of 14 kWh and a lithium-ion pack of 30.7 kWh.

This permits to feed the whole neighborhood under consideration in SS 030 and SS 528 simultaneously during 4 hours approximately while isolated from the main grid and in summer months (this time period of energy supply is diminished in winter). In order to provide 75 kVA peak power, it is considered that there are 25 kVA three power inverters connected in parallel. Two of these inverters would be employed so as to exchange active power with the main grid (i.e. charging or discharging batteries when needed, i.e. providing response to UC01, UC02, UC04 and UC05). The third converter would be employed to solve the above mentioned power quality issues (i.e. UC03). Such strategy provides the PED with enhanced operational flexibility. Internally, two different battery types will be integrated: a lead-acid pack and a lithium-ion one. The main performances of such hybrid solution will be exploited synergistically. Each pack will be integrated into the PED through a dedicated dc-dc power converter.

VI. ACKNOWLEDGMENTS

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