Promotion of higher penetration of distributed PV through storage for all (StoRES)

S. Afxentis[1], M. Florides[1], C. Yianni[1], V. Efthymiou[1], I. Papageorgiou[2], G. Partasides[3], G. Papagiannis[4], G. Christoforidis[5], S. Mocci[6], A. Rubiu[7], J. Oliveira[8], J. Sancho[9], N. Poize[10], T. Pristovnik[11] and G. E. Georghiou[1]

[1] FOSS Research Centre for Sustainable Energy, University of Cyprus, Nicosia, Cyprus
safxen01@ucy.ac.cy, geg@ucy.ac.cy
[2] Electricity Authority of Cyprus (EAC)/Distribution System Operator (DSO), Nicosia, Cyprus
[3] Ministry of Energy, Commerce, Industry and Tourism, Nicosia, Cyprus
[4] Department of Electrical Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
[5] Department of Electrical Engineering, Western Macedonia University of Applied Science, Thessaloniki, Greece
[6] University of Cagliari, Cagliari, Italy
[7] Municipality of Ussaramanna, Sardinia, Italy
[8] Regional Agency for Energy and Environment in Algarve, Algarve, Portugal
[9] SARGA-Government of Aragon, Zaragoza, Spain
[10] Agency for Energy and Environment in Rhone-Alpes, Villeurbanne, France
[11] Municipality of Slovenska Bistrica, Slovenia

Abstract. Electrochemical storage technology and especially battery energy storage (BES) is emerging as one of the fastest growing storage technologies for grid-connected applications. It has an important role to play in the proposed energy transition offering suitable services for domestic and utility scale applications such as the balancing of the intermittent electricity generated by solar photovoltaic (PV) systems. On the other hand, barriers concerning security and financial compensation must be lifted before it becomes a reliable and profitable option. This paper outlines the primary targets of StoRES project towards eliminating the uncertainties related to battery storage. For this purpose, coupled PV-BES residential storage systems will be developed in five countries aiming at optimizing the utilization of storage towards achieving higher PV penetration. The process of selecting the pilot sites in each country is analysed highlighting the importance of the selection criteria. Another focus of this paper is the implementation of a community (social) storage system which will be installed only in Cyprus. This will be connected to the same distribution feeder supplying the local residential pilot systems in order to make a credible comparison between the centralized and distributed storage. In light of the above, a market research was performed in order to determine and compare the system configurations that will be applied for the pilot system design. Finally, the methodology for acquiring and monitoring the data from the pilot sites along with the expected outputs is outlined.

Keywords: Photovoltaics, Energy Storage Systems, Residential storage, Community storage, Energy management, Self-consumption.

1 Introduction

Environmental concerns associated with the reduction of Greenhouse Gas (GHG) emissions have brought electricity production from Renewable Energy Sources (RES) at the front line. This is also reflected in the very latest targets set by the European Union (EU) aiming at achieving a resilient Energy Union (COM(2013)253) [1]. This renders RES a very attractive and viable alternative to fossil fuel generation targeting the decarbonization of the electrical grid and the integration of higher shares of distributed generation. However, further unobstructed distributed generation may impose serious issues to the public grid requiring substantial restructuring of the electricity network. For this reason, the adoption of new technologies is urgently needed to facilitate higher RES penetration and achieve the very ambitious targets set by the EU. For instance, the variable and intermittent nature of RES generation is an important point that makes planning and energy dispatch a very difficult issue to deal with. A solution proposed in the literature and also in the long-anticipated climate and energy framework proposed by the EU (Clean energy for all Europeans) [2] is energy storage which can potentially remove the shortcomings related to high RES penetration and can provide the desirable flexibility and reliability to the existing energy system [3]. Energy storage has an important role to play in the proposed energy transition offering suitable services for several applications both at utility and behind the meter [4]. The capabilities of storage can be used for supporting the grid operation by balancing the variable electricity generation of RES and hence can allow further RES penetration without compromising grid stability [5, 6]. Also, the introduction of Demand Response (DR) and smart energy management strategies can assist in this direction [7].

Nevertheless, battery storage is still lightly used and solutions are at an early stage of development requiring extensive work and trials to meet the needs of the interconnected grid. The most important issue that prevents the deployment of storage is the lack of remuneration for the services it offers and the relatively high unit price. However, considering the rapid decline in the price of RES and especially Photovoltaic (PV) systems [8], and the achievement of grid parity in many parts of the world with high solar resource coupled with decreasing battery prices makes the deployment of storage a potentially viable alternative calling for serious consideration by the involved stakeholders. This is what StoRES is trying to address. The primary target of StoRES is the development of an optimal policy for the effective integration of RES and Energy Storage Systems (ESS). The main challenge is to allow the further deployment of RES and predominantly small residential PV systems in the energy mix of islands and rural areas in the Mediterranean (MED) region. By addressing related technical and financial implications for effective integration of storage systems in the public grid, the substantial utilization of ESS will be enhanced.

A different number of residential pilots will be selected in each of the participating pilot regions (Cyprus, Greece, Italy, Portugal and Spain) where distinctive particularities, needs and requirements will be taken into consideration for the optimal development of common technical solutions. The main objective of StoRES is to boost self-consumption in the aforementioned regions with the integration of suitable storage systems. The coupled PV-ESS solutions will be tested in the different pilot sites and by taking into consideration the different regional specificities, current shortcomings concerning grid reliability from higher RES penetration will be addressed. Following this, different scenarios for optimizing self-consumption will be studied with the most advantageous and beneficial to be developed in order to achieve further RES deployment and to offer a potentially cost-effective and sustainable option. Further to the development of Residential Storage Systems (RSS), StoRES proposes the integration of a Community Storage System (CSS) which will be implemented only in Cyprus in order to perform a valid comparison between centralized and decentralized storage and to explore the potential services that can be offered by such solutions. Finally, the optimum sizing of social and domestic storage systems will be identified for the benefit of all connected users. Possible potential services that can be offered by such solutions will be explored as the first step towards system optimization of the integrated grid.

2 Technical Solution

2.1 Design of joint technical solution

The intention of this project is not to develop new technologies for battery storage but to use existing technologies, evaluate their limitations and suggest new features to enhance them. Therefore, a market research was carried out to identify the existing battery storage system technologies which are combined with PV systems. The research revealed two common types of battery storage systems, the AC-coupled and the DC-coupled.

AC-coupled System. The AC-coupled system is shown in Fig. 1. It is called AC-coupled because the PV and battery power are utilized via a common AC-bus. It consists of a unidirectional PV and a bidirectional Battery converter which are both connected to the grid and the load via the common AC-bus [9]. The PV converter consists of a DC/DC converter, which serves as the Maximum Power Point Tracking system (MPPT), and an on-grid inverter. The Battery converter consists of a DC/DC converter, which serves as the battery Charge Controller (CC) and an on/off-grid inverter [10]. The connection to the grid is made via a bidirectional electricity meter and an optional grid switch.

An operational drawback of this system is that in backup mode the PV converter is able to provide power only if the Battery converter is operating, i.e. if the Battery converter shuts down unexpectedly the PV converter will automatically shut down as well (due to its automatic shutdown function in cases of grid outage, so-called “anti-islanding” feature). Even if the automatic shutdown is disabled, a PV converter cannot provide AC voltage on its output by itself due to its design. It is worth mentioning that if PV power curtailment is required, the Battery converter should be able to communicate and control the PV converter.

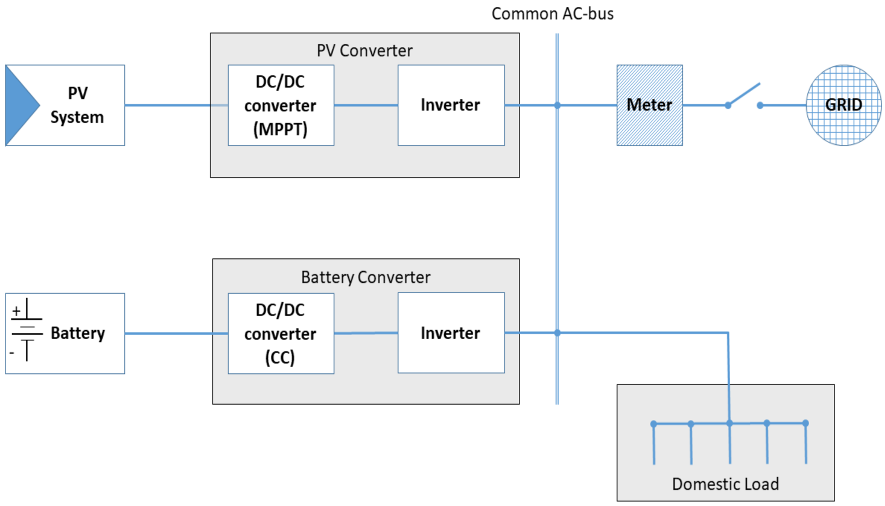

Fig. 1. Schematic diagram of an AC-coupled system

DC-coupled System. Two different DC-coupled systems exist. The first one is called "Retrofit" system and makes use of an existing PV converter and facilitates a charge controller which is responsible for the battery charging/discharging. This type of system can be easily fitted to existing grid-connected applications. However, this solution poses numerous confinements to the system due to the PV converter design and will not be examined in this study. On the other hand, the "Hybrid" system requires only a single power converter which is called Hybrid converter. It is called DC-coupled because the PV and battery power are utilized via a common DC-bus inside the Hybrid converter [9]. The Hybrid converter consists of a PV DC/DC converter (serves as the MPPT), a battery DC/DC converter (serves as the CC) and an on/off-grid inverter [10]. Each of the PV and battery DC/DC converters are connected to the common DC-bus which is then connected to the grid and the load via an on/off-grid inverter. The schematic representation of the DC-coupled "Hybrid" system is shown in Fig. 2. The connection to the grid is also made via a bidirectional electricity meter and an optional grid switch. The DC-coupled system does not have the operational drawbacks of the AC-coupled system in backup mode and also it can curtail the PV power by itself if required.

Both Systems. The meter communicates with the Battery or the Hybrid converter, which serves as the central controller of each system, and regulates the power flow from/to the battery and hence from/to the grid in order to achieve the desired service (Table 2). The grid switch is used to isolate the system from the grid in case of a grid outage and potentially allow backup power to the load from the PV and/or the battery.

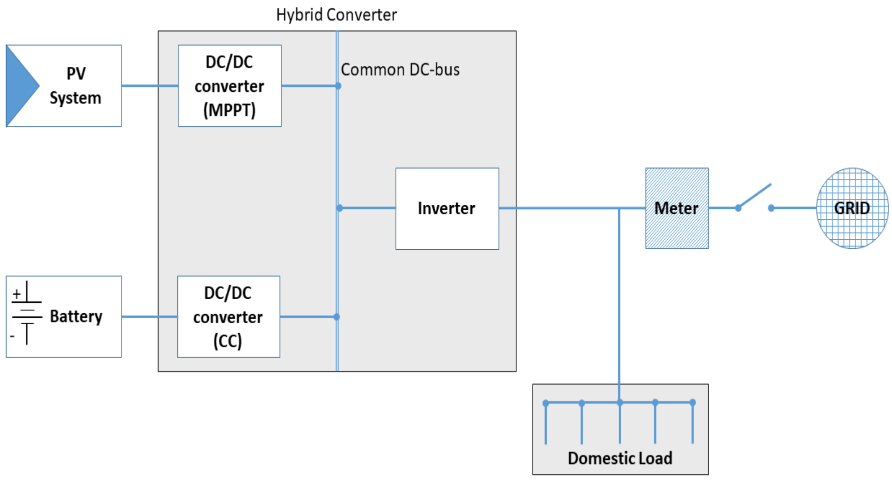

Fig. 2. Schematic diagram of a DC-coupled “Hybrid” system.

AC-coupled versus DC-coupled systems. Table 1 shows the advantages and disadvantages of the two systems; the AC-coupled and the DC-coupled. The main advantage of the AC-coupled system is its easy expandability since more systems can be added in parallel in the future to increase the storage power and capacity. In order to achieve that with a DC-coupled system, the Hybrid converter has to be upgraded as well. Even though both system configurations offer several services including the capability to charge the battery from the grid based on Time of Use (ToU) tariff management, the lower efficiency of the AC-coupled along with the advantages of the Hybrid converter makes the DC-coupled system a favourable option.

Residential Storage. Battery storage systems will be installed at a different number of residential pilot sites in the countries previously mentioned. It is within the scope of the project to test and validate the optimal utilization of storage in order to achieve higher rates of self-consumption and even higher PV penetration. As a consequence, some storage services, such as the backup power, are beyond the scope of the project and hence they can be excluded from the systems that will be installed in the pilot sites. For this reason, both the AC-coupled and DC-coupled configurations are eligible for residential installation. The system sizing including the inverter power and battery capacity and power is different in each pilot country and it was based on the average consumption of the selected households and the available PV production.

Community Storage. The aforementioned solutions are applicable for residential systems. StoRES also proposes the installation of a community pilot site which will be implemented only in Cyprus. The centralized storage system will be installed in a preselected distribution substation and will be connected to a distribution board that supplies the residential pilots. The only applicable system configuration is the AC-coupled system since there will be no direct PV production, meaning that only a battery unit and a battery inverter are required for the system to be connected to the grid.

Table 1. Advantages and disadvantages of AC-coupled and DC-coupled system configurations

	AC-Coupled	**DC-Coupled**
Advantages	• Easily fitted to existing installations	• Fewer components
	• Offers easy expandability	• More efficient
Disadvantages	• Requires both PV inverter and Battery inverter	• Requires the replacement of the existing PV inverter with a Hybrid inverter
	• Battery charge is not supported when the public grid is not in operation	• Expensive to upgrade the storage power and capacity

Storage Services. Many studies in the literature have proven the valuable services and benefits of energy storage to the public grid with the most important being the balance of the intermittent production of distributed generation [11]. More recently, the evolution of electrochemical storage technology promoted Battery Energy Storage Systems (BESS) as an emerging technology that can provide services in many applications. In particular, BESS can provide many services on transmission, distribution and behind the meter (consumer) level. The StoRES project will put emphasis on the services at the distribution and behind the meter levels and targets to test and optimize the services shown in Table 2. The aim is to develop a suitable control algorithm that will manage the on-site energy at the pilot sites in order to achieve higher self-consumption rate and allow further penetration of PV in the energy mix of MED regions.

Battery Technology. The battery technology choice for both residential and community storage is lithium ion (Li-ion). Due to space limitations in the houses, their high energy and power density, high efficiency and durability make them attractive [12] [13]. They also have low self-discharge rate and require minimum maintenance [12]. Amongst the several advantages of Li-ion technology, many issues associated to electrical and chemical hazards exist. These are mainly related to the environmental and operational parameters of the battery system such as the exposure to sunlight, ambient temperature or high electrical current. Nevertheless, the use of a battery management system (BMS) has proven to reduce the risk to a minimum [13] and also to maintain the appropriate operational parameters of the battery [14]. Considering the environmental impacts related to the use of Li-ion batteries, recycling is possible [15] but at the moment is not beneficial due the high cost involved.

Table 2. Proposed storage services for residential and community level

Behind the meter services (Residential)	Distribution level services (Community)
Increase self-consumption	VAR control
Peak shaving	Manage feeder loading
ToU tariff management	Voltage support
Voltage Support[1]	Frequency support[2]
Frequency Support	Optimum sizing of BESS systems in the community

2.2 Selection of pilot locations

The selection of the pilot sites that will house the residential storage systems is the next step. A similar methodology was followed in each participating country to determine the pilot locations and the procedure was organized through liaising with the local authorities of each pilot region in order to ensure the transparency of the process and coherent pilot selection. As a consequence, the main principle that was taken into consideration for the completion of this phase was the homogeneous selection since all pilots must come out as an output of a common procedure. Apart from the pilot selection criteria that were set in each pilot county based on the current regional legislation, the selection was limited to households with existing residential PV system with a typical energy profile and even more to have a balanced energy production and consumption profile. Finally, local specificities and technical needs such as the maximum allowable PV system capacity and eligible system configuration were subsequently incorporated to the selection procedure of each region in order to develop a thorough selection. The selection procedure in Cyprus had to also take into consideration the implementation of both residential and community storage on one electricity distribution feeder. Typical information about the selected pilot sites in each region is shown in Table 3. The diverse PV capacities of the pilot systems highlight the different legislations that exist in each country with various upper limits on the maximum allowable PV installed capacity. The different system sizes will provide a first class opportunity for the study of storage systems under different conditions and interesting findings are expected to arise.

[1] Reactive power (VAr) is injected/absorbed to/from the electrical grid to avoid transmission losses and therefore maintain voltage within an acceptable range (230VAC±10%).

[2] Active power is fed into the grid or excess energy is absorbed from the grid to maintain grid frequency stability.

Table 3. Typical Information of the pilot sites in MED countries

Country	Number of pilot sites	Premise Type	PV system capacity range (kWp)
Cyprus	5	Typical households	3 to 5
Greece	5	Typical Households and Office Buildings	5 to 20
Italy	11	Typical Households	3 to 12.5
Portugal	5	Typical Households	1 to 1.5
Spain	5	Typical Households	3 to 10

2.3 Data Acquisition

Data collection and monitoring is important in order to study the impact of storage in domestic and community applications. Different energy management strategies will be assessed and applied at the pilot sites in order to develop the most efficient methods that will offer higher rates of self-consumption and further increase PV penetration. Towards this end, the different storage services outlined in Table 2 shall be individually and collectively investigated to support grid operation and eventually optimize the energy cost of the prosumers.

Statistically appropriate samples will be selected and monitored during the project duration and it is important to ensure a coherent methodology to record the data in all pilot regions. A common dataset format will be defined for all pilot sites whilst data protection and security will be maintained by applying suitable security protocols. Further to the equipment that will be installed at the pilot sites for the coupled PV-ESS system, additional components will be employed for data collection and monitoring purposes. In particular, at least two Smart Meters (SM) will be installed in each pilot system in order to keep record of the imported and exported electricity to the public grid and also data for the PV system production and household consumption. Another significant data class is the continuous storage unit status that will be extracted by monitoring the battery lifetime, State of Charge (SoC) and power through the battery inverter interface. Further to this, information regarding the grid status and the system performance can be made available either from the system components or additional SMs. In the light of the above, data from the pilot sites shall be recorded at a sampling frequency of 30 minutes and gathered locally to a database that will be developed in each pilot country for further analysis. More specifically for Cyprus, a central database is proposed for implementation by the EAC for the data collection of all pilot sites which will be updated on a daily base. Also, a secondary database is to be developed at the facilities of the University of Cyprus and the information of the central database will be mirrored through a secure communication link. The schematic representation of the communication link design is shown in Fig. 3. To this extent, important data such as the PV system production, the battery SoC and the domestic load demand will be collected and an algorithm will be developed to manipulate the pilot system capabilities. In light of this, optimal charging and discharging points of the battery unit can be detected and also suitable ToU tariffs can be estimated and applied to the EMS system through Modbus TCP/IP connection. Finally, by taking necessary measures in the distribution feeder such as the voltage level and the power factor, the optimal power flow between the residential and community pilots will be extracted to minimize the distribution grid power losses.

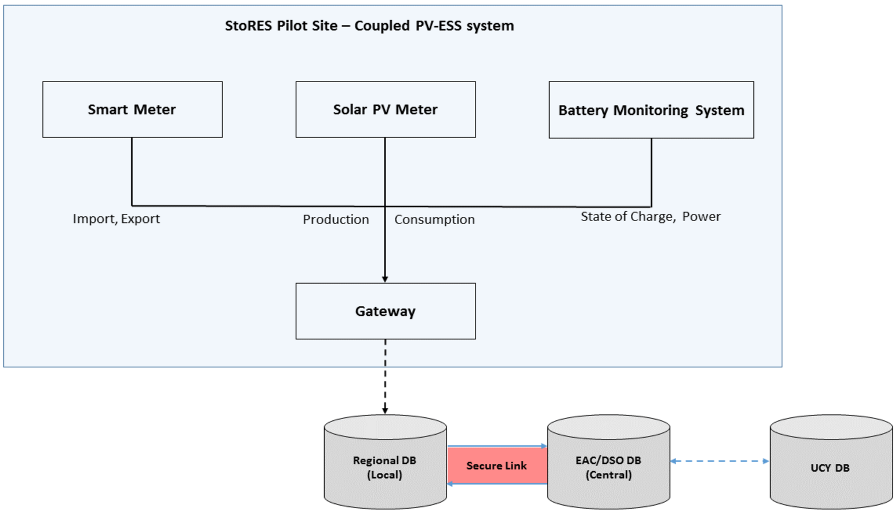

Fig. 3. Communication link between the pilot sites, the local and the central database

3 Expected outputs and conclusions

The proposed systems will be installed at the selected residential premises in each pilot country in order to study the storage functionality and to offer higher shares of distributed generation in the energy mix of the countries. The integration of distributed battery storage units with the existing PV installations will allow even higher shares of PV generated electricity. At the same time, issues related to grid stability and battery storage utilization will be addressed aiming to enhance the resilience of the energy system. The installation of the systems in all pilot locations is expected to be completed within the final quarter of 2017. Communication devices that will be employed along with the coupled PV-BESS system will allow the local monitoring of the prosumer data. Simultaneously, custom made algorithms will be developed for optimally increasing the prosumer self-consumption. Additionally, ancillary services such as voltage and frequency control will be investigated in order to support the operation of the grid. This along with the objective of managing grid congestion will underpin the need of energy storage integration in the future electricity system. Towards this end, possible scenarios that render BESS as a reliable option will be shared with all participating stakeholders, DSOs and policy makers. This will encourage the adoption of new policies that promote higher shares of RES in the energy mix of the participating regions and will pave the way towards structuring a resilient energy system that deploys high shares of distributed RES in which the contribution of BES systems plays a vital role.

Acknowledgement. Project co-financed by the European Regional Development Fund (ERDF) through the Interreg MED Programme.

Disclaimer. This document reflects only the authors' view and the ERDF is not responsible for its contents or any use or exploitation of the information it contains.

References

1. EC, "Towards an Integrated Roadmap: Research Innovation Challenges and Needs of the EU Energy System," December 2014.
2. EC, "CleanEnergy for All Europeans-unlocking Europe's growth potential" Nov. 2016.
3. F. Steinke et al, "Grid vs storage in a100% renewable Europe," *Renewable Energy,* vol. 50, pp. 826-832, 2013.
4. K. Worthmann et al, "Distributed and Decentralized Control of Residential Energy Systems Incorporating Battery Storage," *IEEE Transactions on Smart Grid,* vol. 6, no. 4, pp. 1914-1923, 2015.
5. N. Wade et al, "Evaluating the benefits of an electrical energy storage system in a future smart grid.," *Energy policy,* vol. 38, pp. 7180-7188, 2010.
6. M. Nick et al, "Optimal Allocation of Dispersed ESS in Active Distribution Networks for Energy Balance and Grid Support",," *IEEE Tran. on Power Systems,* vol. 29, no. 5, pp. 2300-2310, 2014.
7. A. Mishra et al, "Smart charge: Cutting the Electricity Bill in Smart Homes with Energy Storage," *Proceedings of the 3rd International Conference on Future Energy Systems: Where Energy, Computing and Communication Meet,* p. 29, 2012.
8. A. Jäger-Waldau, "PV Status Report," EUR 28159 EN; doi:10.2790/682995, 2016.
9. M. Vetter and L. Rohr, "Lithium-Ion Batteries for Storage of Renewable Energies and Electric Grid Backup, Lithium-Ion Batteries,," *Elsevier,* pp. 293-309, 2014.
10. N. Zhang et al., "A review of topologies of three-port DC–DC converters for the integration of renewable energy and energy storage system," *Renewable and Sustainable Energy Reviews,* vol. 56, pp. 388-401, 2016.
11. J. Weniger et al, "Sizing of Residential PV Battery Systems," *Energy Procedia,* vol. 46, pp. 78-87, 2014.
12. IPHE, "Battery Energy Storage technologies for power system," 2012. [Online]. Available: http://www.iphe.net/docs/Events/Seville_11-12/Workshop/Presentations/Session%201/1.3_IPHE%20workshop_Antonucci.pdf. [Accessed 27 April 2017].
13. IEC, "Electrical Energy Storage," 2011. [Online]. Available: http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf. [Accessed 11 April 2017].
14. M. Akdere et al., "Hardware and software framework for an open battery management system in safety-critical applications," *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society,* pp. 5507-5512, 2016.
15. A. Boyden et al., "The Environmental Impacts of Recycling Portable Lithium-Ion Batteries," *Procedia CIRP,* vol. 48, pp. 188-193, 2016.