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Energy storage coupling in a high efficiency household scenario: A real life experimental application

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ABSTRACT

Distributed renewable energy sources and storage could play a key role in the future energy ecosystems, reducing emissions, strengthening grid resilience and improving energy efficiency. Nowadays, several ongoing pilot projects aim at measuring real-life performances of different coupling criteria between RES generators, storage apparatuses and the final users' consumption. In such a context, this paper presents an innovative experimental project led by E.ON Sverige AB in the Hållbarheten residential complex, in Malmö (Sweden). In a modern and innovative apartment, 58 passive loads and 2 local generating units – a PV system and an urban wind turbine – have been monitored. Within the project, real users lived in the apartment and a proactive energy behavior was promoted thanks to a special energy tariff (specifically implemented for the experimental project) and to dedicated media, supposed to easily provide information to the users (e.g. iPad app depicting in real-time energy tariff, energy consumption and production, etc.). In a second phase, a numerical analysis has been carried out to evaluate the effectiveness of the integration of an electrochemical energy storage system in the apartment, testing different control laws, evaluating different technologies and, eventually, proposing a techno-economic analysis.

1. Introduction

In the last decades, a technical revolution occurred in the operation of electrical networks. With the diffusion of Dispersed Generation (DG) and the formulation of concepts such as Smart Grids, new paradigms have emerged in managing electrical systems. Smart Grid is a concept for the digitalization of the grid infrastructure based on intelligent components; it involves all levels of the electric power system architecture, from High Voltage (HV) transmission lines to the Low Voltage (LV) distribution grids [1].

The formulation of this concept arises from the needs that DG, in particular from intermittent Renewable Energy Sources (RES), brings along. DG requires being cost-effectively integrated into the grid, together with consumers' energy demand. The European Directive No. 2003/54/CE [2] defines DG as the aggregation of generating units with a nominal power lower than 10 MW connected to either MV or LV grid.

An interesting point of view on the topic is presented in [3], in which RES are not considered in terms of generating units anymore, but as a source of demand reduction with unique time characteristics. Instead of considering wind or Photovoltaic (PV) as a power source, the report suggests regarding them as a reduction in load, with conventional generators meeting the "residual load" (demand net of the electricity produced by renewable generators). Such a shift in paradigm implies necessarily a change in how the existing mix of power plants should be operated. As a matter of fact, the short-term variability of RES would increase the need for ancillary services [4,5]. In order to withstand such new conditions, flexibility and operating reserves in the system should be enhanced, and one of the possible ways forward is represented by Energy Storage Systems (ESS).

ESS indicates any device that is able to perform a bidirectional energy conversion, extracting energy from an external source, storing it for a certain amount of time, and releasing it back at a suitable moment. For electric applications, the literature also describes ESS as the capability of storing energy and releasing it in periods that are more beneficial due to technical efficiency or economic convenience. From this perspective, integrating energy storage apparatuses to the intermittent injections of DG can offer a valid alternative to the power dispatching via conventional fossil-fueled power plants in terms of costs, quality standards and continuity of service.

While energy storage comes with the benefit of being intrinsically

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Nomenclature

Acronyms

BESS	Battery Energy Storage System
DG	Dispersed Generation
DoD	Depth of Discharge
ESS	Energy Storage System
HV	High Voltage
ICT	Information and Communication Technology
LV	Low Voltage
MV	Medium Voltage
PV	Photovoltaic
RES	Renewable Energy Source
RTP	Real-Time Pricing
SoC	State of Charge
TOU	Time of Use
VAT	Value-Added Tax
WTG	Wind Turbine Generator

Mathematical notations

α_{DOD}	Maximum DoD allowed during the BESS operation
$\Delta E_{Batt}(h)$	Energy exchanged by the BESS during the *h-th* time unit (positive when charging) [kWh]
$E(h)$ and $R(h)$	Respectively, user's expenses and revenue streams at *h-th* time unit [€]
$E_{Loads}(h)$ and $E_{Gens}(h)$	Respectively, overall energy consumption and generation in the apartment during the *h-th* time unit [kWh]
$E_{Batt}(h)$	Energy stored in the BESS at *h-th* time unit [kWh]
$E_{Batt,max}$ and $E_{Batt,min}$	Respectively, maximum and minimum BESS capacity in nominal conditions [kWh]
$E_{Imp}(h)$ and $E_{Exp}(h)$	Respectively, energy purchased and sold from/to the grid at *h-th* time unit, i.e. mismatch between the power generated by DG units, injected by the BESS and absorbed by loads [kWh]
E_{Rate}	E-rate, defined as a constant rate of discharge power relative to the battery nominal capacity
η_{ch}^{DC} and η_{disch}^{DC}	Respectively, BESS charge and discharge efficiencies measured on the AC/DC converter DC-side
η_{PE}	Efficiency of the DC/AC converter of the BESS
$\eta_{Roundtrip}^{DC}$	BESS roundtrip efficiency measured on the DC side
$\eta_{Roundtrip}^{AC/DC/AC}$	BESS AC/DC roundtrip efficiency
$k(h)$	Hourly price of the energy on the market at *h-th* time unit [€]
$k_{ch}(h)$ and $k_{disch}(h)$	Respectively, equivalent number of charging and discharging cycles occurred before the *h-th* time unit
K	Vector of costs components (K_{fix} and K_{var}) of user's electricity bill
K_{fix} and K_{var}	Respectively, fixed and variable cost components of user's electricity bill [€ and €/kWh]
k_{24h}^{low}	Threshold identifying the 40% lowest hourly prices in the following day [€]
k_{week}^{high} and k_{week}^{low}	Respectively, thresholds for the 40% highest and lowest hourly prices in the following week [€]
λ	Power threshold used in the hysteresis logics to dampen the intermittent behavior of BESS during energy arbitrage [kW]
$P_{Batt,max}$	Maximum power exchange admitted for the BESS, function of its state of charge [kW]
$P_{Gens}(h, j)$	Power generated by the *j-th* generator at *h-th* time unit [kW]
$P_{Loads}(h, k)$	Power demand of *k-th* passive appliance at *h-th* time unit [kW]
$\widetilde{R}(h, i)$	Revenue streams related to *i-th* revenue component obtained by the selling of energy to the grid at *h-th* time unit [€/kWh]

flexible, scalable and efficient, pricing plays a key role for its widespread adoption. If storage technologies and – to a certain extent – wholesale electricity prices might not vary sensibly from country to country, it is regional policies and subsidies that decisively shape the business case for the success of energy storage. As a result, in order to effectively assess the profitability of storage technologies in a specific market, it is fundamental to: classify these technologies; define what kind of services they provide on the market; identify which pricing policies or financial products the assessed market – be it national or regional – offers in support of storage technologies.

Typically, energy storage applications can be grouped into two approaches: front-of-the-meter, for centralized application, in a utility-based model, and behind-the-meter, for distributed application, in a final-user perspective. The present work focuses on the latter and, among the different behind-the-meter business models, it focuses on offsetting the final users' demand charges, which is believed to be of customers' interest, although detailed and realistic analyses are needed to evaluate the viability of this approach. In the literature, [6] assessed the cost-effectiveness of residential storage apparatuses for peak shaving in the U.S. scenario. To this purpose, residential demand profiles are simulated by an agent-based, appliance-level demand model in the time domain. [7] studied the exploitation of BESS, coupled with curtailment strategies, in order to increase self-consumption and to perform a peak shaving of households equipped with PV units in Sweden. Only Lead-Acid batteries are considered and no further investigations are made on the effects of energy tariff and BESS control logics on the users' incomes. The sizing and dispatch scheduling of BESS installed in a residential scenario have been also analyzed, with the purpose of minimizing the costs of electricity purchase from the grid. In [8], authors study the problem of the battery sizing in grid-connected PV systems for load shifting and peak shaving services under a TOU pricing regime; but the effect of peak shaving on the electric bill is not considered.

In [9] BESS are used only for shaving peak loads of single houses located in five major regions of Canada. A simple BESS is developed and demand profiles are modeled by the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM). The work focuses on the technical aspects of the problem, not considering the main economics related to the BESS investment.

In [10] a complete demand side management infrastructure is proposed, resulting in good performances, but also in a quite complex architecture. Each appliance is scheduled through an optimization tool, with the consequence that computational effort and ICT apparatuses are relatively high. Similarly, [11] proposes a framework for the development of a complete energy management system for individual residential units and small communities of domestic users, taking into account both the power system and final users' perspectives. BESS are exploited to increase users' flexibility and two optimization models are developed to minimize electricity bills. A linear regression model is proposed to predict the PV panels production, while a stochastic method forecasts home appliances usage. However, the impact of the non-ideality of BESS technologies on the profitability of the investment is not considered; moreover, no in-depth analyses are carried out about the optimal control laws to implement on the BESS.

In a more general view, [12] focuses on applications in low voltage grids, classifying functionalities, control loops, efficiencies and