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Multi-apartment residential microgrid with electrical and thermal storage devices: Experimental analysis and simulation of energy management strategies

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HIGHLIGHTS

- Thermal & electric storage help to match consumption and renewable production profiles.
- Storage increase renewable energy self-consumption and independency from the grid.
- Storage reduce bidirectionality and intermittency of PV production.
- Computational framework for μ grid simulation under different operating conditions.
- The framework can evaluate diverse storage management solutions for future upgrades.

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ABSTRACT

The paper presents the operational results of a real life residential microgrid which includes six apartments, a 20 kWp photovoltaic plant, a solar based thermal energy plant, a geothermal heat pump, a thermal energy storage, in the form of a 1300 l water tank and two 5.8 kW h batteries supplying, each, a couple of apartments. Thanks to the thermal energy storage, the solar based thermal energy plant is able to satisfy the 100% of the hot water summer demand. Therefore the thermal energy storage represents a fundamental element in the management of the residential demand of thermal energy. It collects renewable thermal energy during day-time to release it during night-time, effectively shaving the peak of the thermal energy demand. The two electric storages, on the other hand, provide the hosted electrical subsystems with the ability to effectively increase the self-consumption of the local energy production, thus lowering the amount of energy surplus to be sold back to the grid, and increasing the self-sufficiency of the microgrid. For instance, the storage has supported self-consumption up to the 58.1% of local energy production with regard to the first battery, and up to the 63.5% with regard to the second one. Also, 3165 and 3365 yearly hours of fully autonomous activity have been recorded thanks to the first, and the second battery respectively. On the other hand, the yearly average efficiency amounts to 63.7%, and 65.3% respectively, for the first and second battery. In the second part of the paper we propose a computational framework to evaluate the overall performance of the microgrid system, while accounting different operating conditions and energy management policies. From this perspective, the framework acts as a useful modeling and design tool, to assess the opportunity of employing alternative energy management system topologies and strategies. Eight different configurations, with growing complexity, have been derived from the original system on purpose. The simulations, carried out based on real data related to one-year time period, have provided results showing that, the higher the integration level of electrical and thermal storage is, the higher degree of self-sufficiency can be achieved by the microgrid, and, in turn, the more consistent the yearly energy saving become. Nevertheless, despite the energy cost reduction achievable

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with the availability of storage systems in the Leaf House, their high investment cost made them not really profitable at the current price conditions for devices and energy purchase.

1. Introduction

Power grids are going to face several challenges, such as the increasing diffusion of distributed generation technologies [1–3], many including renewable energy sources [4–7]. Other challenges come from the integration and connection, at local scale, between electric and thermal networks (but also electric mobility in the near future) [8–12]. Moreover, with the adoption of demand side management (DSM) strategies, final consumers are going to play an active role in the grid activity [13–19]. In this context, energy storage technologies have a key role for several reasons. In the first place, they represent the means to match energy production from renewable sources and energy demand [20,21]. Even more so in residential scenarios, since the load profile often describes the typical energy demand of an employee, who needs hot water mainly early in the morning and late in the afternoon, with a minimum contemporary factor with solar production. Thermal energy storage allows to collect renewable energy during day-time and to use it during night-time. In addition, energy storage devices enhance the energy self-consumption level achievable by final users. Thermal energy storages, in particular, help in reducing the burden on service utilities (natural gas or electricity). Electrical energy storages double the benefit. On the one hand, it lowers the burden on the power grid. On the other hand, it reduces, or prevents altogether, depending on circumstances, the bidirectional flux of energy, from and towards the grid. It compensates for the main obstacle against renewable energy source widespread, that is the aleatory nature of renewable energy source availability [22–24]. The third reason, which is related to thermal storage, if tailored on purpose, is the ability to increase the energy yield of solar based thermal energy plants [25]. In conclusion, energy storages improve the flexibility of DSM strategies, enhance the final user energy demand profile, and also minimize the overall energy bill [19,26].

In the transition from nowadays power grid technology to the smart grid technology, microgrids play a fundamental role as small scale test bench of DSM strategies [27–29].

In this paper we present a residential microgrid, the Leaf House, which accounts six apartments, a photovoltaic (PV) energy production plant, a solar based thermal energy production plant, a geothermal heat pump, a thermal energy storage in the form of a water tank of 1300 l and two batteries of 5.8 kW h each. The Leaf House hosts a building automation and monitoring system which makes it an ideal test field for energy storage systems applications. By recording and collecting the data resulting from the everyday life of its lodgers, the Leaf House is a living lab that records real life energy demand profiles. Also the performance of both electrical and thermal storages are evaluated on real life operating conditions, rather than in simulated ones.

A relevant contribution of this work is the computational framework aimed at micro-grid design, which serves as a tool to model and simulate the energy management occurring within the Leaf House electrical system. It has been used to simulate the environment behavior over a one-year time horizon, accounting different storage management strategies and various system configurations. The suitability of computational tools to monitor, control and simulate the smart grid behavior in different operating conditions and at different abstraction levels, has been extensively shown and commented in literature [30–33]. The proposed framework is based on the Mixed-Integer Linear Programming (MILP) paradigm, successfully used for energy management purposes by some of the authors in recent publications [34,35], but not yet proposed as a design tool in the evaluation of case studies based on a real life environment such as the Leaf House. The MILP approach has shown its effectiveness and capability, in dealing with a large number of constraints, with respect to other computational intelligence techniques [36–38]. The framework includes, also, a Neural Network based software for solar power forecasting. The simulations carried out in this work have provided the means to evaluate the yearly energy overall cost for each of the addressed configurations. Therefore, the importance of the electrical and thermal energy storages within the system has been evaluated, but also the fact that the Leaf House energy management system can be improved with the adoption of adequate hardware modifications and storage management strategies.

The paper is organized as follows: Section 2 presents the microgrid used as reference, along with operational results and related comments. In Section 3 the energy management simulation framework and the solar power forecasting algorithm are presented, whereas Section 4 presents the case study and the scenarios being examined. The simulation results are reported and discussed in Section 5. Section 6 draws the conclusions of the work.

2. Microgrid under study: the Leaf House building

The Leaf House (see Fig. 1) is one of the six international case studies selected by the IEA Task 40/ECBCS Annex 52: "Towards Net Zero Energy Solar Buildings" [39,40]. Built in 2008, the Leaf House is located in Angeli di Rosora, Ancona, Italy (latitude 43°28′43.16 N, longitude 13°04′03.65 E, altitude 130 m above sea level). The site is characterized by a moderate climate: annual temperature between −5 and 37 °C; 1688 degree day, mean annual horizontal solar radiation 302 W/m^2. The Leaf House is a three stories building, hosting three couples of twin flats. Two apartments are occasionally occupied, while the remaining four flats are occupied by two lodgers each. The building is south oriented and the ratio between the lengths of the south and east facades was set to 1.34 to maximize solar gains during the colder season. The roof, the solar thermal panels and the balcony have been designed to behave as solar shadings during the hottest months.

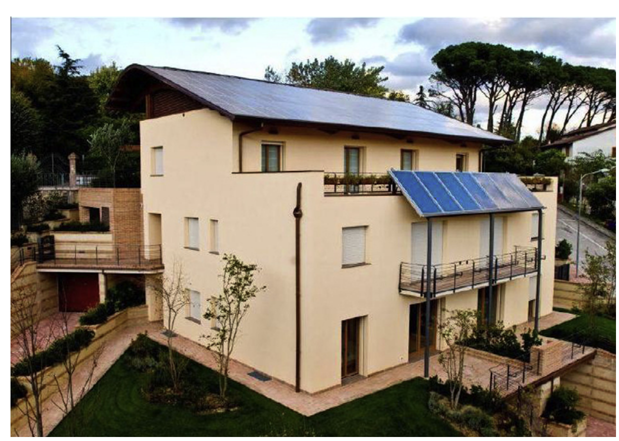

Fig. 1. The Leaf House.