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Improving flexibility of industrial microgrids through thermal storage and HVAC management strategies

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Abstract

The increasing share of non-programmable renewable energy sources in national energy portfolios requires a high flexibility to balance demand and offer in energy markets. Demand side management programs and microgrids will play a key role in achieving flexibility on the demand side. This paper aims at presenting the increase of flexibility that can be achieved by an industrial microgrid. On field tests were carried out in an Italian industrial microgrid, where a set of load management strategies were implemented. These strategies aim at leveraging the thermal inertia of a building using both thermal energy storage and the HVAC system. Results show that the thermal energy storage can contribute to limit the peak cooling load by up to 40 kWe for three hours, while implementing a load shifting strategy using the HVAC system can provide a temporary reduction in power consumption of 20 kWe. Results also prove that it is possible to identify the effect of a load shifting strategy using electricity consumption data sampled with a 15-minutes granularity.

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Keywords: thermal energy storage; demand side management; microgrid; flexibility; thermostatically controlled loads; TLC; thermal mass.

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1. Introduction

In many countries, a large share of the national energy portfolio is now made from non-programmable renewable energy sources, thus is becoming harder to assure the balance between the national energy demand and the offer given today's grid flexibility. Demand side management (DSM) programs are going to play a role in enhancing grid's

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capability to cope with this problem, shifting part of the burden from control to demand [1]. Due to the nature of their loads, and the interest in investing in distributed generation, industrial microgrids are perfect candidates to provide services to the grid or actively playing in balancing the electricity market [2]. In [3], authors presented a methodology to identify interesting industrial applications for demand response. Alcazar-Ortega et al. [4] investigated the demand response potential in a meat industry in Spain, finding that the peak power demand in certain periods could be reduced by 50%.

Having in mind these possibilities, research is focusing on new ways to assess how much power can be shifted, or cut, with respect to the traditional electric consumption patterns and for how long. Energy storage systems (ESS), thermostatically controlled loads (TCL) and Electric vehicles (EV) can be all used to enhance a microgrid flexibility and its potential in providing grid services. Thermal energy storage is a key technology to improve flexibility of final users. Several studies have demonstrated their potential in reducing peak loads or arbitraging price [5, 6, 7]. Thermostatically controlled loads (TCL), from residential refrigerators up to complex industrial scale heat pump units, can be managed to shift their electricity consumption away from peak times. Mathieu et al. [8] estimated that the technical resource potential for Californian residential TCLs is approximately 10-40GW/8-12GWh.

This paper presents the results achieved by implementing a set of load management strategies in an Italian microgrids. A thermal energy storage and the building HVAC system are used to leverage the thermal inertia of the industrial building and the synergy with the microgrid's renewable generation.

This study's central contributions are a set of indications on how these assets can be individually exploited to increase the microgrid flexibility in terms of demand/generation management and a discussion over the limits of a metering infrastructure sampling with a 15-minutes granularity. The rest of the paper is organized as follows: section 2 describes the industrial microgrids, the flexibility assets used in this study and the DSM strategies implemented; section 3 show the main results, authors comments highlight the effect of the implemented strategies and the potential implications industrial site.

2. Materials and methods

This paper aims at presenting the results obtained doing field tests on an Italian industrial microgrid, where a set of load management strategies were implemented.

2.1. The industrial micro-grid

The industrial microgrid used as a test case is the microgrid of Loccioni Group in Angeli di Rosora, Italy. In particular, tests using both the thermal energy storage and HVAC system were carried out on one of the industrial buildings connected to the microgrid, the "Leaf lab", a two-storey building consisting of two distinct areas: the factory (total area of about 2400 m^2) in the inner part of the building and the offices (total area of about 5200 m^2) placed all around it. The building is equipped with a PV system, with a nominal power of 236.5 kW. The cooling and heating demands are satisfied by three heat pumps, for a total capacity of 430 kW. A thermal energy storage is integrated with the HVAC system to store the excess of PV electricity during weekends. When the factory electricdemand is negligible and PV production is available, the thermal energy storage is charged by means of heat pumps. This thermal energy is then used during weekdays to reduce the peak load consumption. An advanced metering infrastructure collects electricity consumption as well as internal comfort parameters (e.g. internal/external temperature, illumination level) with a 15-minutes granularity.

2.2. HVAC system

The HVAC system consists of chilled beams and air handling units as emission systems and of three water-to-water heat pumps (HP1, HP2, HP3) as production units. The AHUs are used for the whole building, including factory and offices, while the chilled beams are used for the offices only. These two systems can work together or separately. Two of the heat pumps (HP2, HP3), which have a nominal cooling capacity of 280 kW each (when supplying water at 7 °C), are used for the AHUs. The smaller heat pump (HP1) has a cooling capacity of 150 kW (when supplying water at 15 °C) and is used for the chilled beams only. Their capacity can be regulated according to the cooling demand by varying the load at 20–40–60–80–100% of the total capacity and the supply temperature ranges between 5 and 15 °C. The water source for the heat pumps is represented by a well at a constant year-round temperature of about 13 °C. The water from the well can also supply the chilled beams directly in passive cooling mode for reduced cooling demands.

2.3. Thermal energy storage

The thermal energy storage consists of an insulated concrete water tank of 460 m^3. It has a rectangular base and its dimensions are 12.3 x 11 x 3.4 m. Each wall has a thickness of 0.25 m and is insulated by means of 0.16 m of xps polyfoam c350 (thermal conductivity 0.032 W/m K). The tank is buried below the ground to reduce heat losses as much as possible. In summer the storage tank can be charged by the heat pumps (HP2, HP3) outside the working hours (when PV electricity is available or during off peak hours, as better explained in the following) and it can supply then cold water to the AHUs when cooling is required during the working hours.

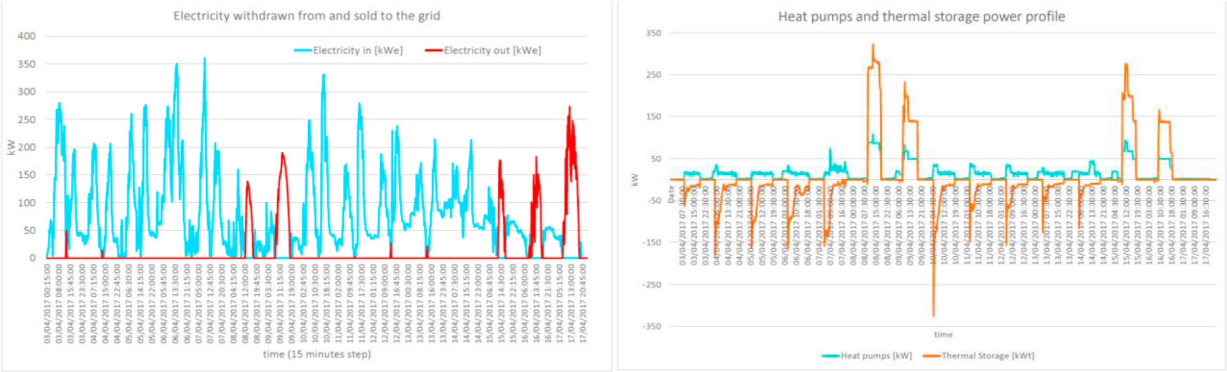
2.4. Demand side management strategies

The first strategy tested aims at assessing the reserve of power that the industrial microgrid could achieve by the integrated use of PV, heat pumps and thermal energy storage. Indeed, the PV plant production, that during working days is almost entirely self-consumed, during weekend widely exceeds the microgrid consumption (Figure 1a): this excess of energy can be used to drive electric heat pumps to charge the thermal storage; then, during the week, the thermal storage can be discharged reducing the usage of heat pumps.

The second strategy aims at assessing the reserve of power that can be achieved by controlling the HVAC system. In particular, heat pumps temperature set points are regulated in order to reduce the electricity demand in certain periods of the day exploiting the thermal inertia of the building to maintain the internal comfort. This can be referred as a load shedding strategy. After the set point change, heat pumps shut down until the temperature reaches the new set point.

3. Results and comments

This section reports the results of the DSM strategies tested in the industrial microgrid. Figure 1b shows the effect on the electricity demand of using the thermal energy storage for two weeks in the month of April 2017. Figure 1a reports the trend of electricity withdrawn from and fed into the main grid, with 15-minutes time steps. The PV production is completely self-consumed during working days, while it largely exceeds the energy demand during week-ends (in red in Figure 1a). When this happens, the exceeding electricity is fed back into the main grid. Thanks to the thermal energy storage part of the electricity produced by the PV plant can be used to drive the heat pumps and accumulate thermal energy. Figure 1b shows heat pumps power consumption (in blue) and the thermal energy storage charging pattern (in orange). The analysis of Figures 1a and 1b allows some considerations. First, the charging phase of the thermal energy storage happens during week-ends simultaneously with the excess of PV production. Nevertheless, part of the PV production is still exceeding and sold to the grid. The monitored period showed in Figure 1a includes Easter week-end: Saturday (15th of April), Easter Sunday (16th of April)and Easter Monday (17th of April). As in the other week-ends, the PV plant drives the heat pump until the thermal energy storage is fully charged. The thermal energy storage discharging phase usually starts on Monday, however on Easter Monday this did not happened. While the thermal energy storage was fully charged, the HVAC system was not operating and all the PV production was sold to the national grid. During working days, the energy discharged from the thermal energy storage allows to reduce the power consumption for HVACConsidering the thermal energy discharged and an average measured heat pumps' COP around 2.8, the thermal energy storage can provide up to 40 kWe of flexible load for three hours. It is worth noting that these tests were carried out in a relatively mild season, thus the thermal energy storage potential is not fully exploited in terms of heat pump power curtailment. Figure 2 reports the trend of the temperature inside the thermal energy storage: the first two days (8th and 9th of April) correspond to a week-end during which it is possible to see the increase of temperature due to the charging phase. The other days correspond to the discharging phase. Once the storage is charged, a slight decrease of the temperature can be observed due to thermal losses; when the discharge phase starts on Monday 10th, the temperature inside the storage decreases suddenly, then when the discharge stops, thermal losses can be distinguished again. For every discharging session, the temperature reduction observed is less than 1 °C.



(a) (b)

Fig. 1. (a) Active power exchanged from the microgrid prospective; (b) Heat pumps and thermal energy storage usage profiles

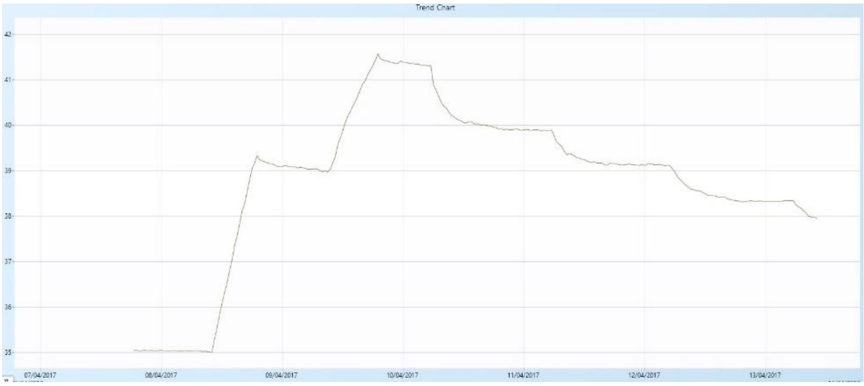
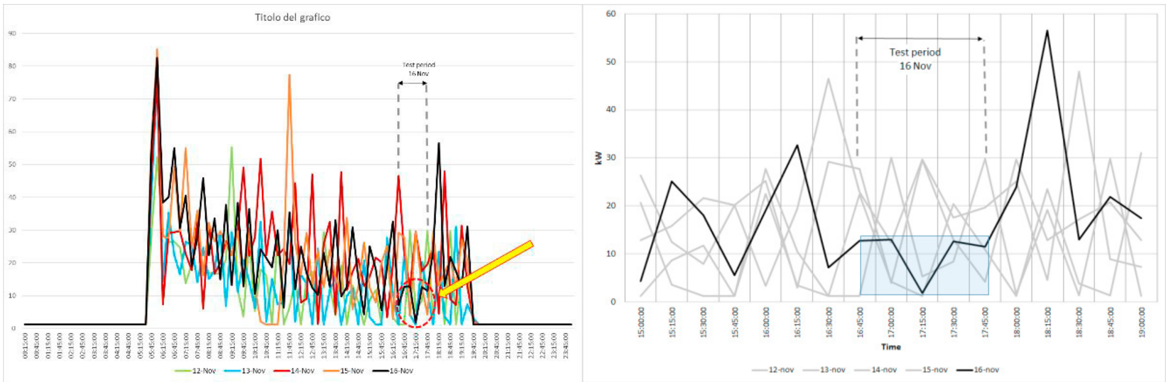


Fig. 2. Temperature inside the thermal energy storage in deg. C

The load shedding strategy was tested the 16th of November during a working day, between 16:45 and 17:45. Figure 3a provides an overall view of the heat pumps consumption profiles during the five working days. The energy consumption time series for the 16th of November is highlighted in black. Figure 3b focuses on the time window during which the test was carried out; the 16th November consumption time series is reported in black, while the other working days are reported in grey. The load shedding test was set for 16:30, in order to be effective from 16:45. After the set point change, the heat pumps electricity demand was indeed reduced by a sensible margin until the new set point is reached at 17:45, when the heat pumps started working again (Figure 3b). The consumption pattern registered during the test is noticeably different from the rest of the week: the on-off cycle, clearly recognizable for grey curves, is interrupted by a longer off period for the black one; a new consumption peak, higher than the ones registered over normal operation regimes, is formed after the heat pumps start working again. This load recovery phase is well known in the literature: after a load shedding period, heat pumps are forced to work extra hard to maintain the desired thermal comfort ending up creating a new peak in electricity consumption. Thus, while the load shedding strategy provides a temporary reduction of around 20 kW in power consumption, the overall effect on the consumption profile is to create a new higher consumption peak (57 kW at 18:15), while increasing the overall energy consumption. Figure 3b shows that another day of the week, the 14th of November, presents a similar consumption peak in the afternoon (48 kW at 18:30). This observation can be explained by looking at the daily average external temperature values showed in Table 1, where peak demand and total energy consumption data are reported for each analysed weekday, focusing the observation from 16:00 until 18:30, around the testing time window. Indeed, the 14 of November was in average a much colder day, a 3 °C difference in terms of daily average which directly results in extra effort for the heat pumps, hence extra consumption.

Results confirm that load shedding strategies can contribute to provide a sudden reduction in power absorption, which could potentially enable a wide range of grid services, however their effect at the single building level is a shift in the load profile, resulting in a new consumption peak and overall worst performance in terms of energy efficiency. This test also proves that sampling electricity consumption data with a 15-minutes time granularity is sufficient to identify the activation of a load shedding strategy and, given a consumption baseline, to analyse its impact in energy terms. However, if the nature of the application requires an estimate of the actual power shedding capability, then higher granularity would be necessary.



(a) (b)

Fig. 3. (a) Heat pumps consumption profile for five working days; (b) Heat pumps consumption profiles focused around the testing time window.

Table 1 Energy, power and average temperature data for the test week

Day	Electricity consumption between 16-18.30 [kWh]	Peak demand between 16-18.30 [kW]	Daily average external temperature [°C]
12-Nov	31	30	8
13-Nov	32	28	6
14-Nov	62	48	5
15-Nov	49	30	8
16-Nov	51	57	8

Future studies will focus on how to evaluate the potential load flexibility granted by the combination of all available micro grids assets, while exploring the integration of new assets and demand management strategies.

4. Conclusions

This paper shows how flexible loads can be leveraged in an industrial microgrid. Two demand side management strategies were implemented using a thermal energy storage and the HVAC system. Tests were carried in the industrial microgrid of Loccioni group, in Italy.

The first strategy aimed at assessing the reserve of power that could be achieved by the integrated use of PV, heat pumps and thermal energy storage: the excess of PV generation during weekends was used to drive electric heat pumps and charge the thermal energy storage; then, during the week, the same storage was discharged reducing the electricity consumption of heat pumps. Results showed that thermal energy storage contributes to curtail the peak load consumption by up to 40 kWe for three hours, in mild season.

The second strategy aimed at assessing the reserve of power that can be achieved by controlling the HVAC system. Heat pumps temperature set points were regulated to reduce the electricity demand in certain moments of the day exploiting the thermal inertia of the building to maintain the internal comfort. Results showed that load shedding via HVAC control can provide a temporary reduction in power consumption by up to 20 kWe, while a new consumption peak is generated right after heat pump reactivation. This test also proved that sampling electricity consumption data with a 15-minutes time granularity is adequate to identify the activation of a load shedding strategy.

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