Aggregation of Users in a Residential/Commercial Building Managed by a Building Energy Management System (BEMS)

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***Abstract*—Buildings with mixed residential and commercial units show relevant power peak that are further increased by shifting from gas-driven systems to an electric source. The proposed solution is to organize a microgrid for such type of buildings, aggregating different users with a common electric distribution system with a single connection to the grid, a local common generation, and a common heating/cooling system (electric driven). This approach upgrades a group of independent small users with rigid loads and chaotic behavior to a large user with a flexible and controlled profile. A central building automation control system managing all built-in technical systems and smart appliances may control the load, minute by minute, shifting in time shiftable and controllable loads, and merging different kinds of loads, obtaining a flatter diagram. The authors consider the suggested approach convenient to realize a demand side management (DSM) for residential/commercial buildings. distribution system operator (DSM) exploits the flexibility of smart appliances and the thermal inertia of the structure, by imposing local and central set points of heating and cooling systems, according to actual global net load and generation at a given moment. In this paper, main aspects of the proposed control system are presented and simulations for a given case study with a local photovoltaic system generation are provided. Results show that this approach may lead to a power peak reduction up to 20% even in the unfavorable case of combining commercial and residential units. Moreover, full self-consumption of locally generated energy from renewable energy systems may be achieved.**

***Index Terms*—Building automation, building energy management systems (BEMS), demand side management (DSM), photovoltaic systems (PVs), microgrid.**

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Abbreviations

BACS	Building automation control system.
BEMS	Building energy management system.
BES	Building electronic system.
DHW	Domestic hot water.
DSM	Demand side management.
DSO	Distribution system operator.
DW	Dishwasher.
GSHP	Ground source heat pump.
HBES	Home and building electronic systems.
HES	Home electronic system.
HIS	Human–system interface.
HVAC	Heating, ventilation, and air conditioning.
LS	Local supervisory.
MSB	Low-voltage main switch board.
POC	Point of connection between a user and DSO.
PV	Photovoltaic system.
RES	Renewable energy systems.
SC	Metering satellite.
SCR	Self-consumption ratio equal to the ratio between self-consumed energy and locally generated energy.
SDMS	Smart distributed metering system.
TBS	Technical building systems.
ULP	Local panel for each unit.
WM	Washing machine.

I. Introduction

Modern buildings are served by many embedded technical building systems (TBS) needed for their operation, both for comfort and safety. Many of these systems are very energy demanding; thus, nowadays, proper management is a priority for energy saving as mentioned in the IPCC 5th Assessment Report, WG III [1].

In the evaluation of the energy performance of a building, the systems that must be considered, according to European rules [2] are heating, ventilation, and air conditioning (HVAC), domestic hot water (DHW), and built-in lighting. Other main energy users in buildings are built-in auxiliary systems (e.g., elevators, surveillance, etc.), appliances, and cooking that together account for 38% of energy end-use [1].

It is well known that energy savings can be achieved via building automation control systems (BACSs), as highlighted in [3]. The impact can be evaluated via the BAC factors [4], [5].

On the other hand, BACSs can be useful for demand side management (DSM) activities at the building level. In this case, the purpose of control systems is not the energy saving, but the energy and economic optimization. DMS activities have the dual purpose of optimizing the load profile for the user and optimizing the energy exchange with the distribution system operator (DSO) [6]–[9].

Technologies for the implementation of smart electric systems in buildings, compatible with BACSs and DSM, are already available, while barriers are mainly in existing regulations.

In general, three concepts for a building's electric system can be envisioned:

1) a traditional system, with single points of delivery for each user;
2) an innovative (microgrid) system, with a central point of connection (POC), with aggregate energy billing and subdivision of energy expenditures among users; this will be considered in this paper as a "microgrid scenario" for the building;
3) a hybrid system with single points of delivery for each user, but with a common energy management of the aggregation of the users.

As shown in previous studies by some of the authors [10], an aggregate energy purchasing and billing is economically beneficial. The benefits can be classified as follows:

1) use of more convenient nonresidential rates;
2) better exploitation of on-site generation;
3) DSM activities;
4) dynamic pricing.

In this case, DSM activities are effective both in the optimization of load profiles with respect to the grid and in the economic optimization for the users.

The aggregate energy purchasing envisions the presence of an entity acting as an energy aggregator, according to various models given in [11]–[13].

Many buildings, especially newly built ones, are equipped with local renewable energy sources (RESs), such as the photovoltaic (PV) system, which may be ceded through the energy supply system. The integration of the local generation implies that an end-user may shift from consumer to producer within each operating period, widening the range of possible power demand/generation values with well-known effects on the power grid. Such shifting of the user may be called "prosumer" to differentiate it from usual consumers (that are always a load for the grid) and producers. The uncontrollable nature of many RES leads to poor efficiency in their exploitation, as upload and download energy rates are very different for end-users. So, proper management is critical to promote RES integration in buildings. Moreover, domotic systems are available and their use is spreading in new and renewed dwellings, both as built-in systems and as intelligent appliances. These technologies permit users to monitor electricity consumption and to actively control loads in private homes, or even remotely by smart devices, whereas usually these controls are managed independently by each individual apartment. In this scenario, it has been shown by Gottwalt *et al.* [14] that a single domestic user can expect rather low profits of an investment in smart appliances. In previous papers [15] and [16], opportunities in prosumer performance enhancement through DSM provided by smart appliances in full-electric buildings (i.e., buildings in which heating services are provided through electric-driven heat pumps) have been shown. An electric microgrid is suggested, which is served by a single POC with the distributor. Microgrids are electrical distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads), which can be operated in a controlled, coordinated way. The suggested microgrid approach may upgrade hundreds of individual households in a building/district with the opportunity to integrate DSM of private households. This requires integrated building automation controls. Commercial users have load profiles quite different from residential users [17]. In this paper, we investigate the effect of the integration in a local grid of commercial users, as apartment buildings and districts often include shops. It is well known that the presence of automatic controls improves the energy performance of the building [3]. The opportunities to improve energy performance brought by the management of a residential/commercial building as a large user are investigated. The most relevant load controlled by the BEMS is heating/cooling that serves HVAC and DHW systems. The power needed for an ambient temperature control is limited by the thermal inertia of the building. As such, energy is more relevant than the instant power for these systems, so it is possible to shift power demand in time by using the building itself as thermal energy storage. Preliminary studies, such as those of Kensby *et al.* [18], have shown that this approach is very promising.

In the proposed control strategy, BEMS may force room setpoint temperatures and system set points, according to the actual global net load and local RES generation. Moreover, power demand due to smart appliances in dwellings, such as dishwashers and washing machines, may be managed via shifting starting times.

A case study, provided by a newly built residential/commercial building, has been simulated by the authors to evaluate the impact of the proposed control strategy for the BEMS on energy performance.

II. BEMS AND DSM

Usual building management system (BMS) expanded to include energy performance (thus named BEMS) may be further developed to provide an active load control to flatten the power-demand profile and improve self-consumption of power from local RES.

Often, a single consumer in a building has only a few controllable loads, limiting the energy effectiveness of control [19]. Aggregation of users at a single POC with the grid allows to improve the energy management of the building in order to reach up an optimal value of flexible demand and to develop a more virtuous and controllable aggregate load demand, so that locally generated energy can be fully consumed on site.

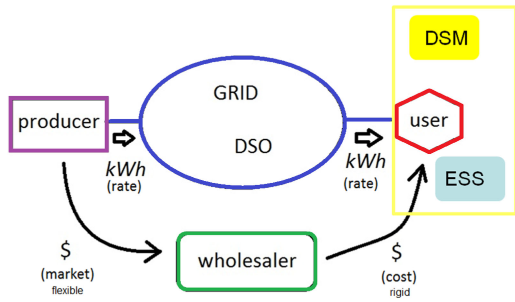

Fig. 1. Traditional scenario without generation.

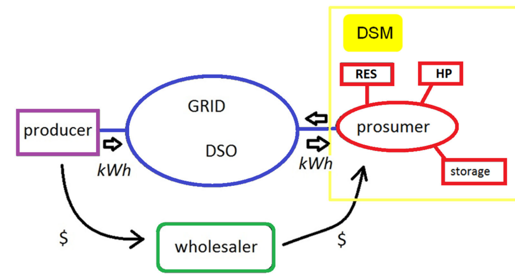

Fig. 2. Microgrid scenario for a single unit.

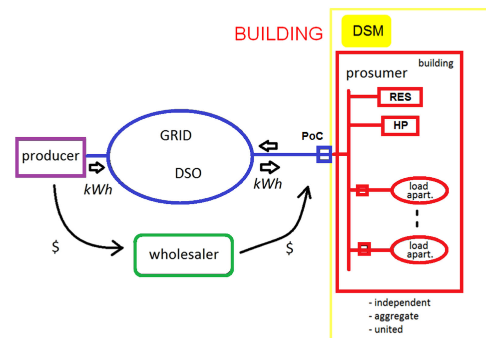

Fig. 3. Microgrid scenario for a building.

Thus, the suggested architecture for the TBS of a residential commercial multiunit building is a full electric microgrid with a single POC to the network. Essentially, the complication of TBS needs a superior architecture for the power system to overcome the rigid scheme of the traditional approach toward an adaptive microgrid. A BEMS is needed to control and manage the TBS, allowing the implementation of advanced DSM logics. The microgrid management is operated with regards to the whole building (large user) rather than of a solitary self-governing small end-user. The natural aggregation is at building level with a high voltage/low voltage substation. A smart grid can be designed as a cluster of smart buildings considered as a single large user.

1) Traditional Scenario—No Generation

In a traditional scenario without local generation (Fig. 1), in the electricity markets characterized by rigid energy prices, DSM may be useful for users only for peak control to avoid a black out. In this case, a DSM is advantageous only for the DSO. For example, in the Italian market, the energy cost is divided in three different rates during the day/week, but with a very low difference of value. In this case, DSM cannot provide cost savings for the consumer. It may become slightly favorable for consumers only if the cost of the energy is flexible, like some electricity market, with great differences of costs according to the time, even though the shortage of controllable loads limits much of its cost effectiveness [14].

2) Microgrid Scenario—Single Unit

In a single unit system with the presence of local generation, the advantages for the prosumer become important even if the cost of energy has a rigid daily profile as it is possible to further exploit locally generated energy with the DSM. In this case, a solution may be to add local electric-storage units (Fig. 2); however, they are currently quite expensive and their use is regulated. However, their use appears to be almost mandatory for effective DSM as there are few controllable loads often.

3) Microgrid Scenario—Building

In a multiunit building scenario, there is a microgrid at building level that is connected to the DSO network in a single POC and serves shared systems and individual units. Aggregating different users, the controllable power is usually higher than the available power from RES. This means that DSM may be an alternative to electric storage units to reach a full self-consumption of locally generated electricity. Moreover, overall heat capacity of the served units is higher; so, it may be expected that at almost any time, there would be some thermal zones in which it would be possible to force a variation of ambient temperature, to store thermal energy, without provoking discomfort to inhabitants. In this scenario, as heat is generated by electric-driven heat pumps, this thermal storage is a controllable load, expanding the potential of the DSM. Merging different varieties of users, such as commercial and residential, leads to a broad range of control opportunities to be explored. In this case, BEMS is needed to fully exploit the locally generated energy (Fig. 3).

III. Architecture of TBS

The suggested architecture of the microgrid is a full electric system. The building is completely gas free as all systems are electrically supplied.

Electric power system: The suggested microgrid consists of an innovative electric-power system characterized by the following:

1) a single POC to the DSO at the HV level and a substation HV/LV;
2) a low-voltage main switch board (MSB) to supply both the common services (heating, elevators, etc.) and the units;
3) a common PV installed on the roof of the building and connected to the MSB;
4) a distribution power system from the MSB for all common TBS;
5) a feeder distribution from the MSB supplying each unit by an independent feeder in a radial scheme;
6) a ULP for the local system.

HVAC and DHW systems: HVAC and DHW are served by a central heating and cooling station with electricity-driven heat pumps. Heating, cooling, and DHW distribution are shared, with a central thermal storage. Each unit is equipped with a metering satellite (SC). Heating energy demand of the building is limited by the thick insulation of the envelope.

The system requires a BACS to improve its effectiveness.

BACS/HBES: The TBS are flanked by a BACS, also called Home and Building Electronic Systems (HBES), that can use an open standard [20]–[22].

The complete architecture of the HBES is divided into the following two systems:

1) Home electronic system (HES)
2) Building electronic system (BES)

HESs are independent local binary unit systems (BUSs) for single houses. Each HES controls technical systems (lighting, alarms, blinds, heating, etc.) in the unit by smart actuators, locally and independently, and is completed with an LS. An HES is operated by inhabitants to control all home systems and appliances through a human–system interface (HIS). The HIS is a software loaded on a client device (e.g., tablet or smartphone) that operates the LS.

BES is the backbone for BUS that connects all the HESs to the main supervisory system, where the general BEMS is uploaded. More details can be found in a previous paper [16]. Smart appliances are integrated in the system with the Transmission Control Protocol/Internet Protocol (TCP/IP) network or a cloud architecture.

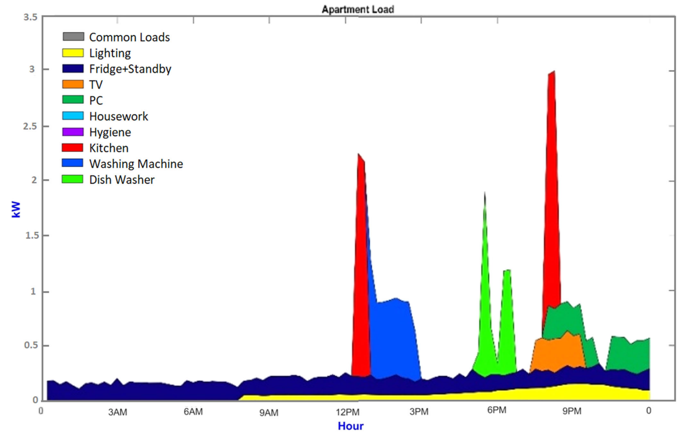

Fig. 4. Single apartment load profile.

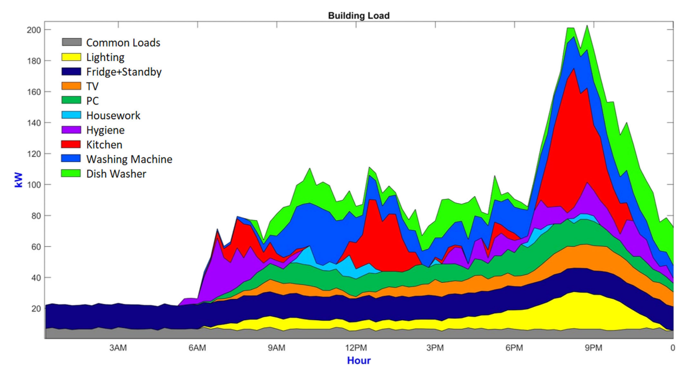

Fig. 5. Load demand example of residential units as a whole.

IV. Loads Demand Analysis

Electric loads may be divided into three categories—uncontrollable, shiftable, and controllable.

Shiftable loads are those that derive from the operation of systems and machines that may be shifted in time, up to some limits, without dropping in user satisfaction; however, once they are started, they become uncontrollable until duty cycle ends. In the present study, washing and dishwasher machines are considered as shiftable loads. There are many more, less relevant shiftable loads, e.g., empty elevator rides.

Controllable loads are those that may be modified at any time, with some limit for the single machine at a time scale lower than the 15-min slot used in energy evaluation. In this study, heat-pump operation is the main controllable load, promoted through the central control of local ambient and system set-point temperatures. There are many other less relevant controllable loads, e.g., refrigerators.

All other loads, lighting, cooking appliances, information and communications technology (ITC) devices, etc., are uncontrollable. That is, any change in the operation of these systems would lead to a drop in user comfort.

A complete bottom-up model of these systems has been developed. Electric devices are defined by their peak load, duty cycle, and energy demand in a 15-min period. Their actual load is simulated with a statistical approach for the presence and the habits of the users. These are also used as input parameters for the heating and cooling model of the building, together with climate data. Heating and cooling loads are used to simulate the operation of the central thermal-energy storage and of heat pumps. Local ambient temperature is proportional-integral (PI) controlled. Heat pumps operate at almost fixed power, with 40 kW heating/cooling output steps. Each step corresponds to a compressor of each unit. Actual power output and input depends on the temperature of water coming back from the centralized thermal storage, too. More details on these models may be found in a previous paper [16].

First, conventional system use, without BEMS, has been simulated. The model generates a reference single-unit residential load profile (Fig. 4). The suggested model [16] allows to obtain an aggregation of many dwellings with stochastic occupation and use, that is the building load profile at the POC (Fig. 5). The inclusion of commercial units in a local microgrid leads to a load profile similar to that shown in Fig. 6. The commercial unit load profile is characterized by a high load, during opening hours, and a very low load for the rest of the day (standard shops have been considered as others, such as catering and crafts, have much different load profiles, which would reduce the general nature of the research). Moreover, there are no shiftable loads as the electricity is used mainly for lighting. In addition, as ventilation rate in commercial units is much higher than in residential ones, HVAC loads are less controllable as the power needed for outdoor air heating is uncontrollable. Note that the actual

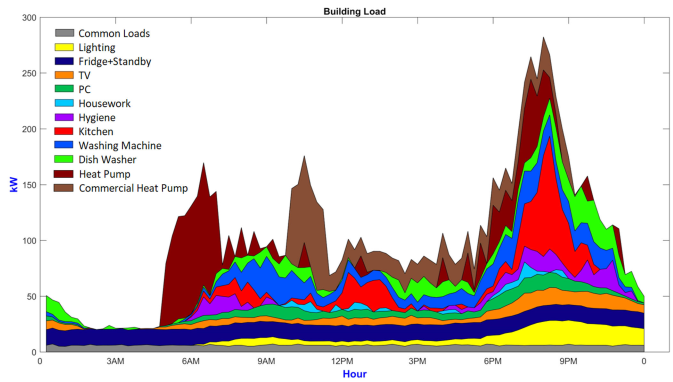

Fig. 6. Example of a load demand of a building with residential and commercial units.

Fig. 7. Case study building.

combined POC load profile depends on the relative extension of the commercial and residential units.

The case study is a residential/commercial building located in Campobasso in the inner part of southcentral Italy. The building is composed of two apartment towers, named A and B, with a common basement that is used for commercial units and parking. Fig. 7 shows the case study building. The region, where the case study is located, can be considered a mildly cold region; therefore, the ventilation and heating systems of the residential units and the commercial area are using an HVAC system.

V. Case Study

Tower A includes 92 small apartments with an average floor area of 50 m^2. Tower B includes 72 medium-sized apartments with an average floor area of 75 m^2. The three levels of the basement are divided into commercial units with 2000 m^2 floor area, and 2000 m^2 for parking. Each tower is served by a couple of elevators, apart from those for the basement. The building is completely gas free as all systems are electric driven. Heating and cooling for both towers and the basement are provided by a station with three reversible ground source heat pumps (GSHPs), each with 86.4-kW-rated heating power and 120-kW-rated cooling power. The electric power absorbed by the GSHPs in each station is between 45 kW [coefficient of performance (COP) of 6.0] and 90 kW (COP of 3.0), according to the actual COP, which depends on the temperature of the ground probes.

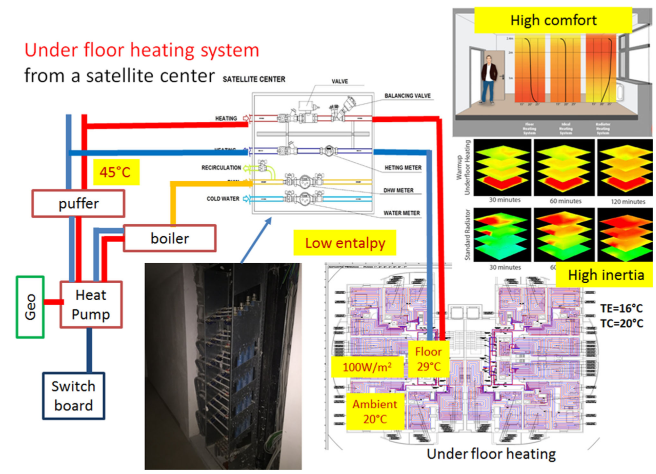

Fig. 8. Sketch of residential heating system and the DHW.

TABLE I
Electric Power Demand

	max	average
	kW	kW
Tower A	100	60
Tower B	100	60
Commercial	80	50
GSHPs A	70	40
GSHPs B	70	40
GSHPs C	70	40
Parking and other	10	10
Global	500	300

Ambient heating in the residential units is provided through floor heating. Each unit is served by the centralized mechanical ventilation, with intake in the bathrooms and continuous operation.

The kitchens are electric. So, the maximum power of each apartment can reach the value of 6 kW, even if it is 50/75 m^2.

Commercial units are equipped with four-pipe fan coils. Mechanical ventilation is provided for each single unit, which operates only during opening hours.

As the parking area is open on the sides, neither ventilation nor heating is provided in these areas.

SCs are equipped with meters for heating DHW and cold water (Fig. 8). An electricity meter is installed in the main switchboard of each unit. The SDMS is connected by the binary unit system (BUS) to the central supervisory system.

Table I shows the global load demand expected equal to about 350–500 kW (average peak demand).

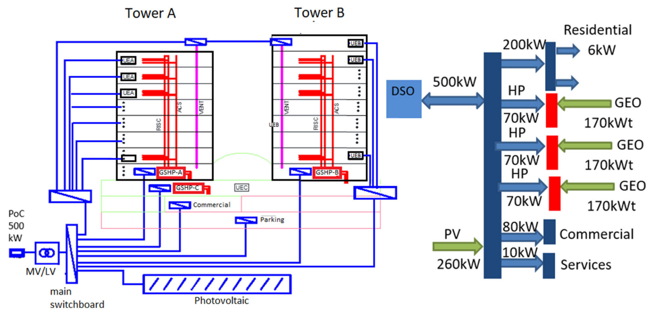

Fig. 9. Proposed smart microgrid.

A PV system is installed on top of the towers, with 260-kW-rated power. Fig. 9 shows the scheme of the proposed smart microgrid.

The building is fully wired with an HBES system.

Each residential unit is equipped with a smart dishwashing machine, a smart washing machine, electric cooking devices, a refrigerator, and other usual domestic appliances. Electric load in the commercial unit is almost entirely for lighting.

VI. Suggested DSM

A DSM is suggested to be operated by the BEMS.

The scopes of the DSM are as follows:

1) maximizing self-consumption of the PV electricity;
2) minimizing power peaks;
3) fitting electricity demand to prices, controlling the net global demand at the point of connection.

The goal is to minimize the electricity bill.

The value of DSM is higher with more dynamic cost of electricity. In a future scenario, DSM would make possible to optimize the performance of an electric-vehicle charging station connected to the microgrid.

The proposed BEMS controls heating and cooling set-point temperatures, and in particular:

1) boilers and puffers set-point temperature;
2) comfort and economy set-point temperatures of each unit;
3) actual ambient set-point temperature of each unit;
4) activation of heating and cooling in the commercial unit.

The BEMS controls also the smart appliances connected to the same (dishwashers and washing machines). This may be done even by traditional appliances with an application for smartphone that signals the best time to run the cycles. Obviously, this is cheaper and simpler, but would be less effective as the human factor reduces the quality of timing. So, it has been not considered in the simulations. The control is performed by adopting simplified rules for the two kinds of smart appliance:

1) the DW cycle must end before the prospected time;
2) the WM cycle must end approximately at the prospected time.

The overall rule for the BEMS is to preserve users' comportment, free to use the services and appliances at will [23].

Other controls can be implemented as follows:

1) the refrigerator, to avoid peaks;
2) empty runs of elevators.

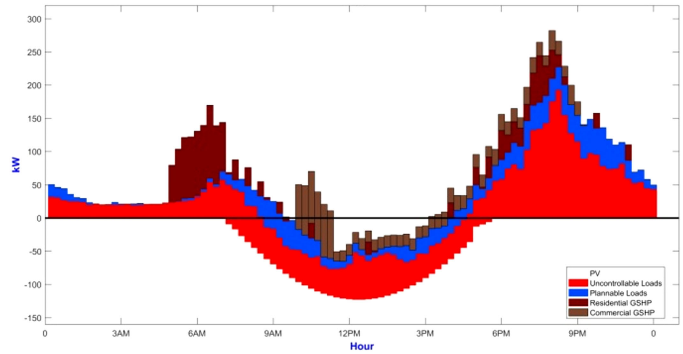

Fig. 10. Load profile, no central control (N).

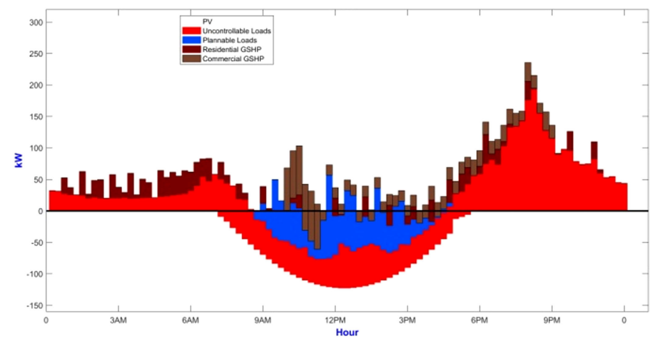

Fig. 11. Load profile, full central control (C).

Suggested refrigerators control (RE): The suggested control manages refrigerator's operation. In the buildings, 164 refrigerators are present. The compressor starting time may be delayed up to a few minutes in case of electric peak due to other loads, or moved up in case of low peak demand with refrigerator temperature close to restarting set point. Moreover, the starting times of the compressor of the refrigerators are scheduled to avoid simultaneous starting.

Suggested elevators control (EL): The suggested control manages the empty runs of elevators. Return runs are done off-peak, exploiting reductions in overall load. During the reentry period, the system would bring the elevators to the ground floor. In the morning and other mostly outgoing periods, it would bring them to an intermediate level, calculating weight and the presence of people at different floors. During other periods, it would keep one elevator at the ground floor and the other at an intermediate level.

At the end, the BEMS manages the following:

1) nine GSHP operations;
2) three storages of DHW;
3) three heating storages;
4) one cooling storage;
5) 164 thermostats;
6) 164 smart dishwashers;
7) 164 smart washing machines;
8) 164 smart refrigerators;
9) four elevators.

The suggested architecture allows to upgrade several small users with a rigid behavior in a flexible large user with hundreds of controllable kilowatts by a BMS. Not all proposed actions

TABLE II
IMPACT OF THE CONTROLS ON THE ENERGY BEHAVIOR

		November		December		January		February		March	
		N	C	N	C	N	C	N	C	N	C
Peak Power Pp	kW	285	215	277	208	302	246	282	205	291	206
Peak Reduction ratio	p.u.	-	0.76	-	0.75	-	0.81	-	0.72	-	0.71
Daily energy consumption	kWh	2260	2148	2548	2316	2927	2737	2530	2298	2512	2467
Daily Energy Reduction ratio	p.u.	-	0.95	-	0.91	-	0.94	-	0.91	-	0.98
Residential GSHP Energy	kWh	221	127	421	303	661	547	414	298	371	270
Commercial GSHP Energy	kWh	199	198	312	314	458	458	307	307	305	305
Daily Energy from grid	kWh	1509	1358	1980	1744	2245	2051	1724	1458	15175	1448
Grid Energy Reduction ratio	p.u.	-	0.9	-	0.88	-	0.91	-	0.85	-	0.95
Equivalent hours	h	7.9	10	9.18	11.12	9.69	11.11	8.9	11.2	8.61	11.95
Self-Consumption	kWh	752	791	568	571	682	685	806	840	994	1019
Grid Feeding	kWh	39	0	3	0	3	0	35	0	25	0
SCR	p.u.	0.95	1.00	0.99	1.00	0.99	1.00	0.96	1.00	0.97	1.00

have been implemented in the simulations, like those that are known to have little influence on overall energy demand.

VII. RESULTS BY SIMULATIONS

Simulations have been done with two limit cases—no central control (N) and full central control (C). In the first case, each system is locally controlled according to fixed set points and all appliances are directly driven by users. In the latter, full control is ceded to the BEMS on TBS, while smart appliances are used with the most accommodative profile, which allows up to a 24-h delay. Different intermediate cases may be analyzed, but these have been chosen as they are most significant to highlight potentials and limits of the proposed approach.

Results show that the control is particularly effective during the daytime in fully exploiting on-site PV generated power and during the evening mealtime, in order to avoid contemporaneity between cooking loads and other appliances.

The effect of the loads due to the commercial unit has been investigated. It has been found that without control, there is a sharp power peak at the evening reentry (already known), when residential and commercial loads sum up. However, this makes a very important improvement of load profile through time shifting of shiftable and controllable loads possible. Lunch breaks add value to the control, reducing the mean required time shifting of appliances, with further improvement of the overall behavior. On the contrary, extended opening hours partially vanishes control opportunities, requiring more collaborative users as load must be shifted to night time to reduce day-time power peak. Building load profiles are shown in Figs. 10 and 11 on a sunny day in February, without and with the central control, respectively.

The impact of these controls on the electric system performance has been evaluated for the characteristic sunny days in winter period, as shown in Table II.

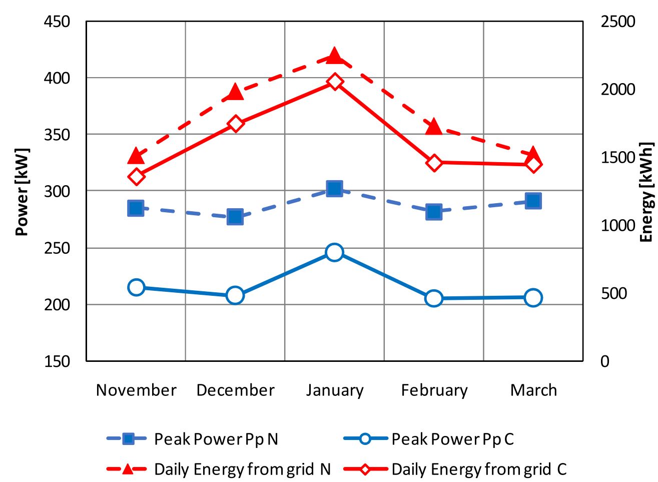

Fig. 12. Peak power and energy from the grid for sample days during the heating period.

BEMS results to be effective on self-consumption of locally generated energy, being able to avoid any shifting of the POC from the consumer to the producer. Moreover, it is very relevant on peak-power reduction. Peak power with and without control depends on the season as heat pumps are a relevant part of the whole load; yet, control is a little bit more effective at the end of the heating season, as shown in Fig. 12.

Moreover, the analysis of the contributions of residential units and commercial units to the whole load shows that the latter is almost nonsensitive to control.

VIII. CONCLUSION

The suggested approach, consisting of the aggregation of the small users of a building or a cluster of buildings in a large user, supplied by a common microgrid with a single POC, has proven to be effective and permits an optimal energy management through load control, which is otherwise not possible. The suggested model upgrades a group of independent many small users with few rigid loads, of low value and with a cumulative chaotic behavior, to a large single user with a flexible and controlled profile and a high value of power.

The contribution due to aggregation of residential and commercial loads has been analyzed. Results show that the advantage of this approach is mainly in the increase of overall load that allows full self-consumption of locally generated power. In the sample case of aggregation considered in the simulations, the impact of the control is more important about the reduction of the peak power than the self-consumption. The results show that the aggregation permits to obtain a SCR of almost 100%, also without control. The control is very effective in the reduction of the peak power with values of 25%–30%. This is due to the higher peak power from the combination of commercial load with residential ones that may be effectively reduced by collaborative power management through the BEMS.

The study presented in this paper is a first approach to a wide problem that should be further studied. The adopted models should be improved to ensure a more realistic behavior that must be validated with real-time operation as soon as the case-study building will be fully operational.

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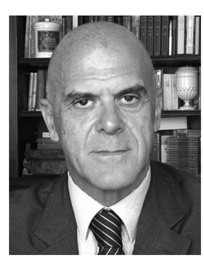

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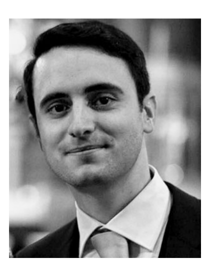

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