

# Electrical energy savings through efficient *cooperation of urban buildings*: the smart community case of ‘Superblocks’ in Barcelona

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**Abstract-** The major challenges that urban living faces over the last years, as a result of the increasing population density, have triggered the discussion for the development of effective solutions that target the economic, social and environmental sustainability of urban areas. Besides, environmental concerns have stressed the need for the development of innovative solutions for the effective and flexible utilization of the renewable energy. In this article, we study the benefits of cooperation as an alternative solution to the optimum management of the energy generated, stored and consumed in urban buildings. The proposed cooperative energy management scheme is applied to a group of smart buildings of diverse energy consumption patterns that form a cluster and exchange energy, so that an optimum utilization of the energy generated by local renewables is achieved. Moreover, we demonstrate the applicability and effectiveness of the cooperative energy management system on a representative Superblock of Barcelona, since the idea of *building cooperation* is inspired by the Barcelona’s unique smart community planning model; the results indicate the significant reduction of the power management cost (32.52 percent in average) and the carbon emissions (62.88 percent in average) compared to the no power-exchange case, due to the optimal utilization of the energy from renewable sources.

**Index terms:** *energy management; cooperative systems; smart community planning; renewable energy systems; energy storage systems.*

## I. INTRODUCTION

It is estimated that over 70 percent of the world's population will live in cities or surrounding areas by 2050. This continuous urbanization trend together with the restructure of the world economy have initiated significant challenges for cities and restated their role as key national or even international economic engines. In this new environment, cities struggle to remain competitive in order to attract investments, increase their tourist appeal and provide better services to their citizens. Information and Communication Technologies (ICT) allow effectively tackling these challenges and providing the means for economic development, for social and environmental sustainability, as well as for high quality of their citizens' life [1].

A multitude of *smart* technologies and solutions have been proposed or even become available over the last years with the target to provide improved service delivery and reduced environmental impact to the citizens. Examples include traffic management and control [2], provision of healthcare services [3], and green growth initiatives. Predominantly strategic for the realization of the future smart cities is the energy sector, which can be transformed to a Smart Grid by incorporating the ICT advantages in the power grid [4]. This evolution, together with the significant reduction of the cost of Renewable Energy Sources (RES) and Energy Storage Systems (ESS), has stimulated the development of environmental-friendly and cost-efficient solutions for small-scale power networks that interconnect urban buildings and target to reduce their dependency from the main distribution grid.

In this article, we investigate the potential of urban building clustering as an alternative small-scale smart community solution, where the participants are able to *cooperate* by utilizing an Internet of Things (IoT)-based platform, in order to increase their energy self-sufficiency and to decrease the city's CO<sub>2</sub> emissions. In our proposed approach, buildings are equipped with RES and ESS, which can be appropriately coordinated in order to achieve minimum energy

1 dependency from the main distribution network. For achieving this objective we propose a novel  
2 cooperative technique, which determines the optimal capacities of the RES and ESS, as well as  
3 their optimum power management by incorporating the buildings' energy consumption patterns,  
4 their seasonal variability, as well as electricity prices and CO<sub>2</sub> emission taxes. Moreover, the  
5 proposed cooperative energy management system goes beyond the state-of-the-art by considering  
6 a group of residential, commercial, and public buildings (e.g. offices, schools, sport centers, etc.)  
7 with diverse energy consumption patterns that are capable of exchanging energy at different  
8 consuming periods on the basis of their energy consumption habits, in order to maximize their  
9 self-sufficiency. Our proposal is controlled by a cloud-based platform that ensures the reliable,  
10 secured and efficient communication among the buildings.

11 The main objective of the proposed cooperative approach is to investigate the potential of  
12 energy sharing as an optimal tool for smart communities to attain a significant reduction of the  
13 buildings' energy dependence on the main distribution grid, as well as of the buildings' carbon  
14 footprint. This objective can be effectively achieved by directing the energy from buildings with  
15 energy surplus to buildings with energy deficit, instead of being sold back to the main grid. The  
16 proposed energy sharing approach also contributes to a more efficient operation of the buildings'  
17 cluster compared to conventional energy management systems, by reducing the energy storage  
18 losses, since the excess energy is consumed by neighboring buildings, instead of being stored.  
19 Moreover, the proposed scheme can determine the optimal equipment capacities, (i.e. the size of  
20 RES and ESS), which guarantees the buildings' self-management and, at the same time, ensures  
21 that all buildings equally benefit from their participation to the cooperation scheme by applying  
22 the Nash bargain method. The proposed cooperative energy management system is evaluated by  
23 considering a representative *Superblock* of Barcelona; Superblocks are "small urban villages"  
24 that have been defined as a part of an ambitious smart-community plan of the municipality of

Barcelona, where the main objectives are to reduce air pollution, to confine noise levels and to encourage citizens to walk and cycle more than using their cars. The application of the proposed cooperative energy management system resulted in a significant reduction of the management and operation cost of the Superblock by 32.52 percent and of the carbon emission by 62.88 percent, compared to the case where buildings do not exchange energy and cover their demands from the main grid only.

The rest of the article is organized as follows. First, we present the Superblock concept as one of the main approaches of the city of Barcelona for reorganizing public spaces. Next, we tackle the main features of the cooperative energy management scheme. Subsequently, we evaluate the performance of our proposals to justify their effectiveness and, finally, we summarize the main conclusions of our work.

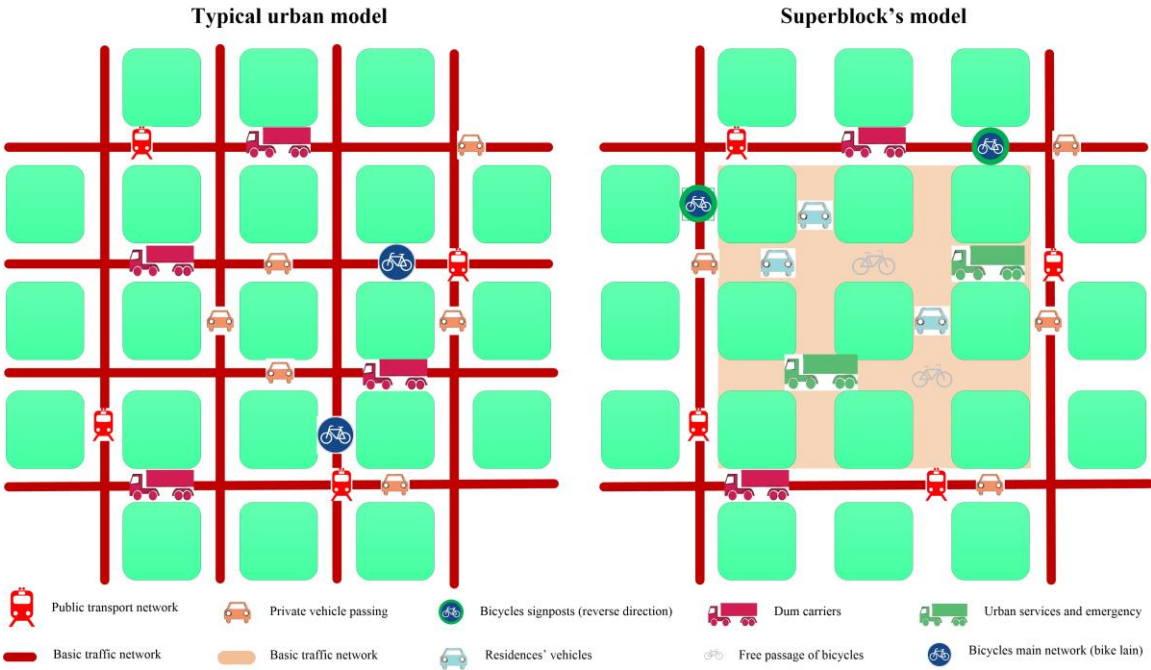


Fig. 1. Typical urban vs. Superblocks planning model.

## II. THE SUPERBLOCK CONCEPT

After the significant urban renewal movement before the 1992 Olympic Games, Barcelona is currently in the process of implementing an ambitious Sustainable Urban Mobility Plan, which targets to define guidelines for the re-organization of mobility and public spaces, with the clear focus on sustainability. The main objective of this plan, which is proposed by the local authority *Agència d'Ecologia Urbana de Barcelona*, is the implementation of Superblocks as a novel way to restructure the typical urban model [5]. The Superblock model goes beyond the traditional geographic and demographic principles for urban planning by reserving road space between city blocks for pedestrians and bicycles, as illustrated in Fig. 1. A Superblock is an urban unit, bigger than a building island and smaller than a neighborhood, with pacified streets. Therefore, the inner roads of a Superblock are mainly used by pedestrians; however, they can be used by emergency/supply services and residential traffic under specific circumstances. On the other hand, the typical urban traffic continues to use only the exterior roads of the Superblock.

The implementation of the Superblock model targets not only to increase the space for pedestrians and the accessibility for people with special needs, but also to improve environmental parameters related to the quality of life of residents and visitors, such as the air quality and the acoustic comfort. For example, the implementation of the Les Corts Superblock in Barcelona is planned to increase the pedestrian space by 50 percent, while it will also result in 28 percent air quality improvement ( $< 40 \mu\text{g}/\text{m}^3$   $\text{NO}_2$  emissions) and 3 percent acoustic comfort improvement (sound level  $< 65$  dBA). Furthermore, the Superblock model promotes a more sustainable mobility behavior by encouraging citizens to walk, use bicycles and the public transportation, which in turn limits traffic congestions. On the other hand, the application of the Superblock model requires changes in the urban planning, such as the restructuring of public transportation network, bicycle lanes, urban parks, surface/underground parking and the management of goods'

1 distribution. However, the implementation cost of the required modifications is not significant  
2 compared to the advantages that the Superblock model offers to the citizens and to the public  
3 authorities [5].

4 The Superblock, as an innovative smart-community model solution and an integrated  
5 ecosystem vision is also able to improve the city's management and organization according to  
6 environmental and citizen needs, especially in the area of energy management. A Superblock has  
7 the optimal dimensions to test innovative smart grid solutions and represents a good opportunity  
8 to apply ideas and projects that can be replicated later in the entire city. This potential is also  
9 amplified by the fact that the Superblock model promotes the installation of RES on public  
10 buildings, while residential and commercial building owners are encouraged to shift from fossil-  
11 fuel based energy resources to green and sustainable solutions. The Superblock program of  
12 Barcelona has set ambitious targets regarding the improvement of buildings' self-sufficiency (by  
13 40 percent), the reduction of electricity cost (by 35 percent) and peak electricity demand  
14 reduction (by 20 percent) to administrative-public and residential buildings. Nevertheless, the  
15 fulfilment of these objectives poses several technical challenges in control, management and  
16 operation of the Superblocks as autonomous smart-grid implementations. Such objectives can be  
17 met by incorporating resourceful energy management systems that are able to ensure an  
18 economical, reliable and secure operation, as well as to save energy especially during peak  
19 demand periods ([6]), while their effectiveness can be optimized through the application of the  
20 IoT paradigm, since an *urban IoT* is able to provide monitoring, control and management  
21 services that are vital smart-community functionalities [7].

### III. COOPERATIVE ENERGY MANAGEMENT SYSTEM

The provision of more efficient building energy management systems requires a systematic and detailed description of the energy consumption patterns, as well as a thorough depiction of the energy generation patterns from renewable energy sources and/or batteries installed in the buildings. The stochastic nature of energy consumption/generation patterns, together with other uncertainties and correlations, are limiting factors of existing optimization models that target the minimization of energy consumption and/or the optimal use of the generated energy [8]. The optimal demand/generation control should also consider that in urban areas the distinction of residential, commercial and industrial consumers is vital for the extraction of the optimal solution. The efficient cooperation of these consumers, as well as the consideration of other factors such as weather conditions, diverse consuming periods (e.g. working hours or holidays for the commercial/industrial cases) and the buildings' energy footprint are key aspects that should be jointly considered to obtain the optimal solution, especially in dense urban areas.

#### *A. Related work and contributions*

The determination of the optimal size of a group of urban buildings has been the subject of several research efforts, mainly through the organisation of the buildings as small-scale power networks, i.e. microgrids. The majority of these studies target to determine the optimal size of the RES either by minimizing the total energy cost ([9]) or by maximizing the energy obtained by the RES ([10]). However, these approaches neglect the benefits of building cooperation on the optimal building energy management; the latter feature is considered in a number of recent studies ([11]-[12]), where the target is to determine the optimal operation plan of cooperative smart homes. The performance of these cooperative schemes is however limited by the fact that they are based on a single buildings' type which have the same power consumption pattern. On the other hand, the optimization approach of [13] targets to determine the optimal microgrid size

and the operation plan of the microgrid buildings, which, however, have to be connected to the same distribution transformer. It is therefore essential to determine both the optimal size and the energy operation plan of a cluster of buildings under a full set of realistic assumptions, in order to maximize the potential of energy self-sufficiency of urban buildings.

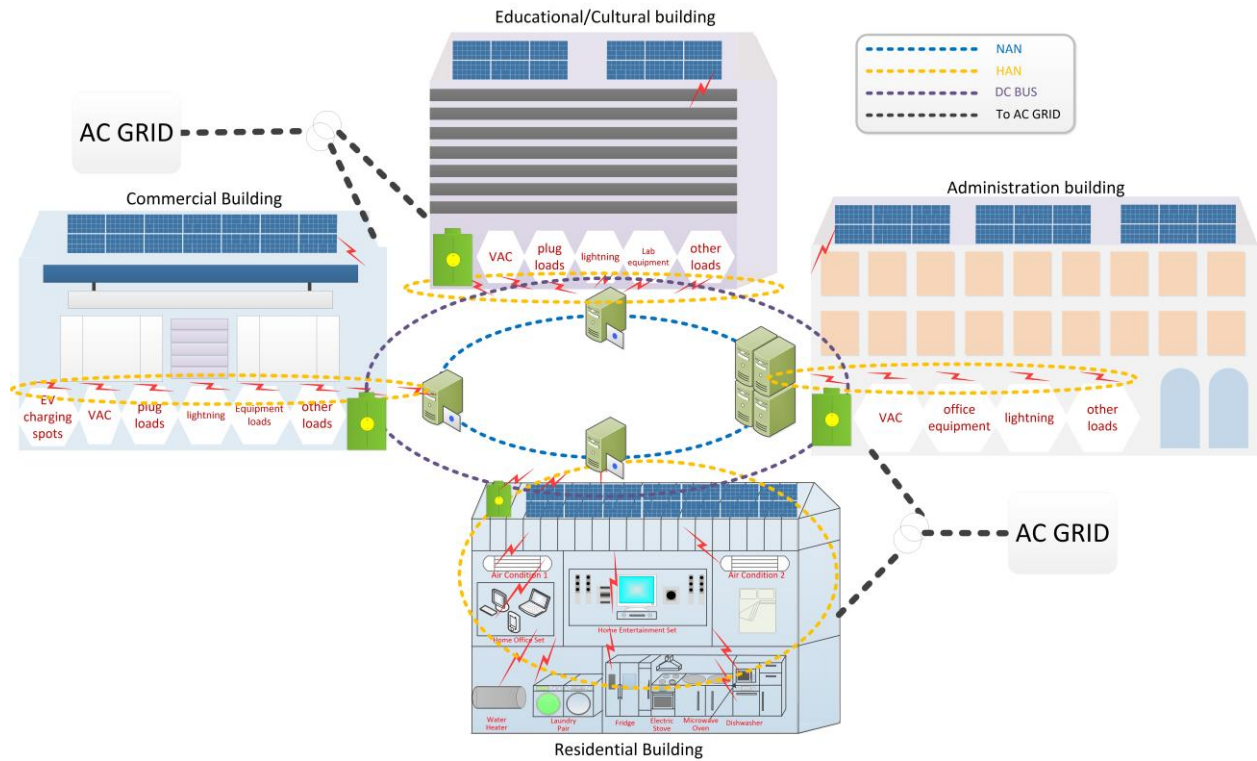


Fig. 2. Power and communication network of the cooperative energy management system.

To this end, in this article we propose an efficient approach to reduce the urban buildings' dependency on the main distribution network, where buildings with diverse energy demands and energy consumption patterns exchange the energy that is generated in the buildings' PhotoVoltaic (PV) units. Precisely, we consider different building types (residential, commercial, administrative, etc.) that form a cluster of buildings, which can be connected to the same distribution transformer through a smart interface to control the power flow, as depicted in Fig. 2.



1 Additionally, the proposed cooperative scheme can be also applied to a cluster of buildings that  
2 are connected to different distribution transformers; in this case, the various buildings are  
3 interconnected through a DC bus, which enables the power exchanges among them. This  
4 configuration enables the application of the proposed cooperative energy management system not  
5 only to the Superblock case, but also to any microgrid case where buildings are connected to one  
6 or multiple power transformers. Furthermore, all buildings are equipped with PV units, which are  
7 connected to the building's loads, to an ESS that is installed in the building, as well as to the  
8 distribution network. Apart from the ESS, the cooperative method also incorporates Electric  
9 Vehicles (EVs) as additional energy storage systems that are able to provide their stored  
10 electrical energy in to the buildings when needed.

#### 11 *B. Superblock's Communication Infrastructure*

12 The communication requirements of the cooperative scheme refer not only to the  
13 communication infrastructure of each building, but also to the network of buildings. In the  
14 building domain, an IoT-based infrastructure is considered, by means of a Home Area Network  
15 (HAN), consisting of smart meters that are installed in different segments of each building and of  
16 a Home Central Controller (HSS), which is responsible for actions such as measuring energy  
17 usage of specific loads and sending/receiving real-time information to/from the loads and the  
18 RES/ESS of the same building. Due to the fact that the smart meters and the other HAN nodes  
19 may have diverse power availabilities, while they may be placed in different locations of the  
20 building, a multi-standard HAN could be implemented. Based on the directions of the  
21 cooperative system, the building's controller is responsible for the energy exchange procedures.  
22 Specifically, depending on the building type, the different power demands, the electricity prices  
23 and the time of the day, the controller makes decisions on how to optimally use the energy  
24 generated by the solar panels, and/or the energy stored in the batteries, which will be either used

for the buildings' needs, for the charging of the batteries of the same or of the neighbouring buildings, or it will be delivered to the main distribution grid. All building controllers form a Neighborhood Area Network (NAN), while they are coordinated by a Superblock Central Controller (SCC), which is responsible not only for the coordination of the energy exchanges among the buildings of the Superblock, but also between the buildings and the main distribution grid. The SCC can be implemented as a cloud-based platform comprising of a message dispatcher for performing secure bi-directional communication, of a database and a corresponding data management unit that will store and manage the cooperative data, and of a configuration unit that determines the optimal management of the buildings' energy. In this way, significant requirements are fulfilled, such as interoperability, scalability, flexibility and security, while a layered architecture can be achieved in order to support the different layers of the Superblock's electrical and communication network. Furthermore, due to the fact that the NAN is deployed in an open public area, while its topology is a function of the characteristics of the applied Superblock, the HCCs may form a low-cost, high-data rate IEEE 802.11s-based wireless mesh network, or, in cases with longer distances between the buildings, the HCSs may be connected through an existing infrastructure of a wired network or an LTE mobile network. In both cases, a reliable and high-speed NAN can be implemented, while security issues can be managed by applying both prevention methods (encryption and authentication schemes for integrity and confidentiality) and intrusion-detection and recovery methods in order to enhance the protection of the infrastructure.

### *C. The proposed cooperative energy management system*

The primary energy sources for each building that are controlled by the cooperative system are their own PVs, ESS and EVs. However, in case of energy shortage, buildings are able to buy energy from the other buildings and/or from the distribution grid. In order to promote

1 cooperation among the buildings, the price for the energy exchanged between members of the  
2 same Superblock should be lower than the corresponding price for buying energy from the  
3 distribution grid. By taking into account the aforementioned considerations, the cooperative  
4 system is able to determine not only the optimum energy management of the Superblock, but  
5 also the optimal capacities of the equipment (PVs, ESS, inverters) to be installed in each  
6 building. Based on the optimal Superblock sizing (the determination of the optimal Superblock's  
7 energy capacity values), the system also determines the daily operation plan, i.e. the optimal  
8 energy exchanges, which in turn is highly affected by the Superblock's sizing. This relation is  
9 expressed by an optimization model that targets to minimize the total cost of each building's  
10 equipment. The total cost includes the installation, maintenance, and replacement cost of the  
11 equipment, the cost of buying energy from the distribution grid and the other Superblock  
12 buildings, the cost due to the CO<sub>2</sub> emission taxes, as well as the revenue of each building due to  
13 the power that exports to the Superblock and to the distribution grid. Finally, both the optimal  
14 Superblock size and the daily operation plan are obtained by applying a method that is based on  
15 the Nash bargaining method, in order to achieve an equal distribution of the cooperation benefits  
16 in terms of cost and CO<sub>2</sub> emissions reduction among the Superblock buildings. The Nash bargain  
17 method targets to eliminate any occasion where some Superblock participants gain extra benefits  
18 against other participants. This is achieved by maximizing the product of savings of each  
19 building, where the savings refer to the difference between the total cost when buildings are not  
20 able to exchange energy minus the total cost when power exchanges among the buildings take  
21 place, instead of using the common procedure of minimizing the total cost. The following steps  
22 summarize the optimization procedure of the proposed cooperative energy management method:

- 23 1. Determine the power balance of each building by defining how the building's power demand  
24 is satisfied (from PVs, ESS, main grid and/or power exchanges);

2. Define the PV, the ESS, the EVs and the inverters operation of each building, based on the equipment and the building characteristics;
3. Define the Superblock power exchanges by equalizing the energy bought from one group of buildings to the energy sold to the remaining buildings' group;
4. Define the total cost of each building of the Superblock;
5. Determine the optimal equipment capacities and power management of the Superblock, by i) defining the savings of each building due to the power exchanges, ii) linearizing the total savings via logarithmic differentiation, and, iii) maximizing the resulted function, subject to the superblock constraints and to the logarithmic differentiation method constraints.

#### IV. CASE STUDY RESULTS

The effectiveness of the proposed cooperative energy management system is verified through its application to the Poblenou Superblock (Fig. 3), which is located in the Sant Martí district of Barcelona. The case study considers six buildings of the Poblenou Superblock, namely two residential buildings (595 m<sup>2</sup>, 945 m<sup>2</sup>), two schools (1100 m<sup>2</sup>, 1458 m<sup>2</sup>), one administrative building (450 m<sup>2</sup>) and a cultural center (1751 m<sup>2</sup>). The values in the parentheses indicate the available surface on each building for installing PV panels. These buildings were considered in this case-study due to their diversity regarding their power consumption patterns; residential buildings usually consume more power during afternoon/evening hours, while the peak demand is observed during the morning hours for the administrative building and one school, and during the afternoon hours for the cultural building and the second school. In each building 1 kWp of PVs is installed for every 7 m<sup>2</sup> available surface with efficiency 0.95, while the hourly PV production of a 1 kWp PV array located in Barcelona is also taken into account. Furthermore, each building is also equipped with an ESS and an inverter, with efficiency 0.95 and 0.9, respectively, while the two residential buildings are equipped with vehicle-to-home systems in

order to support energy exchanges between EVs and the building. The proposed approach takes into account the electricity rates of the energy distributor [14], as well as the Spanish carbon tax, which is equal to 0.03 €/kg. The price that each building sells energy to the distribution network is 90 percent lower than the corresponding network electricity rates, while the rates for buying and selling energy among the Superblock users is 40 percent lower than the corresponding network rates. Furthermore, we consider that the residents of each residential building owns 15 EVs, each one of 24 kWh battery capacity with 0.95 efficiency, 6 kWh charging/discharging rate, while the values of the EVs' state of charge range from 0.3 to 1.

In order to evaluate the design mode of the proposed energy cooperation scheme, we consider the financial data of [9] and [15] for the acquisition, replacement and maintenance cost of the PVs, ESS, inverters and the DC bus. To this end, we study two scenarios: the default scenario, where all buildings obtain the required electrical energy only from the distribution grid, and the cooperation scenario, where the proposed cooperation scheme is applied. In both cases, the optimal design of the Superblock's buildings is realized by considering a project lifetime of 20 years [9], as well as a discount rate of 3 percent. For both scenarios, an optimization solver is defined for the corresponding optimization procedures by considering the Nash bargaining method. The derived results indicate that the optimal equipment capacities of the Superblock are obtained for the cooperation scenario with a significant reduced cost and CO<sub>2</sub> emissions, compared to the default scenario. The capacity values of the PVs, ESS and inverters of each building are provided in the legend of Fig. 3. Specifically, the application of the cooperative scheme resulted in an average 45.16 percent reduced equipment and power management cost for the two schools compared to the default scenario, while this value is equal to 32.38 percent for the two residential buildings in average, 40.06 percent for the administrative building, and 32.37 percent for the cultural center. Furthermore, the CO<sub>2</sub> footprint of the two schools is reduced by

73.5 percent, of the residential buildings by 45.4 percent, of the administrative building by 65.5 percent and of the cultural center by 74 percent, in average, compared to the default scenario. These results indicate the significant impact of the high utilization of the RES and the energy exchanges, which are considered in the energy cooperation scheme, both on the buildings' design cost and on the CO<sub>2</sub> emissions.

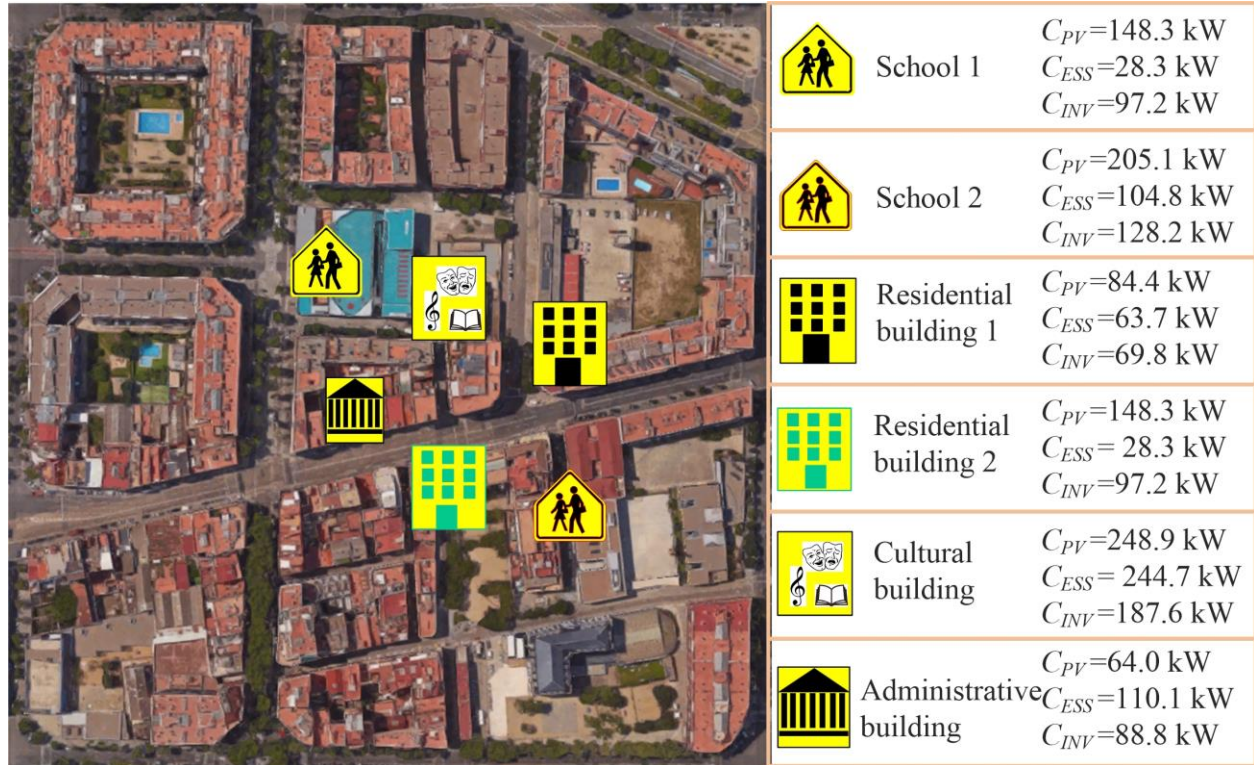


Fig. 3. Overview of the Poblenou Superblock with the six buildings considered in the case-study scenario, together with the results of the optimization procedure for capacities of the PVs ( $C_{PV}$ ), the ESSs ( $C_{ESS}$ ) and the inverters ( $C_{INV}$ ) installed in each building.

The diverse power consumption patterns of the Poblenou Superblock buildings create a high power exchange potential, which may decrease the buildings' dependency on the distribution network, as well as the CO<sub>2</sub> emissions. This fact is highlighted in Table I and Table II, which present the energy exchanges that occur between the buildings on an April's Friday and Saturday, respectively. Specifically, the weather data of 15<sup>th</sup> and 16<sup>th</sup> April 2016 in Barcelona

1 were taken into account in order to model the energy generation process of the PVs. For  
2 presentation purposes, the results of only one of the two schools and one of the two residential  
3 buildings are presented in Table I and Table II, since the energy exchange patterns of buildings  
4 of the same type have similar characteristics. Both tables present the energy consumed by the  
5 corresponding building, as well as the energy that is either stored (to ESS or EVs) or sold (to the  
6 distribution network or the other Superblock buildings). Also, the notation  $P_{A \rightarrow B}$  is used in the  
7 legend of both tables for denoting the power exchanges, where  $A$  is the source and  $B$  is the  
8 destination of the exchange, e.g.  $P_{SB \rightarrow Bld}$  denotes the energy that is provided by the Superblock  
9 (SB) to the corresponding building (Bld). As the results of Table I and Table II reveal, the power  
10 exchanges are highly affected by the type of the day: during Friday, the two buildings with high  
11 energy consumption during daylight hours, i.e. the school and the administration building, use  
12 most of the energy generated by the PVs for their current energy needs ( $P_{PV \rightarrow Bld}$ ), while only a  
13 small portion of the PV energy is used to charge the ESS ( $P_{PV,SB \rightarrow ESS}$ ) or it is sold to the  
14 distribution network ( $P_{Bld \rightarrow Gr}$ ) or to the other Superblock buildings ( $P_{Bld \rightarrow SB}$ ). On the other hand,  
15 the energy needs of the residential building are low during morning hours; therefore the PV  
16 energy is mainly used either to charge the building's ESS ( $P_{PV,SB \rightarrow ESS}$ ) or is sold to the grid and to  
17 the other buildings of the Superblock ( $P_{PV,SB \rightarrow ESS}$  and  $P_{Bld \rightarrow SB}$ , respectively). However, during  
18 early morning hours or evening hours, where the residential energy consumption is high, the  
19 building uses either the energy stored in the ESS or the EVs ( $P_{ESS \rightarrow Bld}$ , and  $P_{EV \rightarrow Bld}$ , respectively),  
20 or the building buys energy mainly from the distribution network ( $P_{Gr \rightarrow Bld}$ ), since the residential  
21 building requires energy during night hours, while then the other buildings use their stored  
22 energy primarily for their own needs. Furthermore, the large surface of the cultural center allows  
23 the generation of large amounts of energy by its PVs, which are used for the building's own

needs, as well as for charging the ESS or is sold to the distribution network and to the other Superblock buildings.

TABLE I: POWER EXCHANGES FOR THE SCHOOL BUILDING, ADMINISTRATIVE BUILDING, RESIDENTIAL BUILDING AND CULTURAL CENTER BUILDING, DURING THE FRIDAY OF APRIL 15TH IN 2016

Administrative building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	6.5	6.5	6.5	6.5	6.5	6.4	5.6	6.4	5.9	13.8	45.5	16	12.4	14.6	13.6	15.5	45.5	22.8	3	38.9	32.5	2.5	13	12.9
	Power stored/sold (kW)	-	-	-	-	-	-	-	-	-	-	55.5	-	-	-	-	-	33.3	-	-	9.5	-	-	-	-
Residential building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	4.9	4.9	4.9	9.8	9.8	24.5	38.1	31.9	2.5	14.7	9.8	9.8	4.9	4.9	4.9	9.8	14.8	19.6	8.4	58.9	63.9	18.5	19.7	0.8
	Power stored/sold (kW)	-	-	-	-	-	-	-	-	4.9	20.6	29.1	29	38	32.1	19.3	33.1	23.2	11.5	3.3	30.5	-	-	-	-
School building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	13.9	13.9	13.9	13.9	13.9	13.8	66.9	27.5	32.8	16.2	9.5	2.5	97.7	97.7	97.7	97	10.5	24.2	44.8	36	13.9	14	14	14
	Power stored/sold (kW)	-	-	-	-	-	-	-	-	-	-	17.3	-	6.5	2.4	5.7	53.2	-	-	-	-	-	-	-	-
Cultural center building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	15.3	15.3	15.3	15.3	15.3	14.9	11.5	9.3	45.1	45.1	60.1	60.1	90.2	90.2	90.2	0.45	90.2	10.9	41.7	105	105	83.8	105	45
	Power stored/sold (kW)	-	-	-	-	-	-	-	-	36.5	62	10.4	57.3	13.8	17.9	21.1	28.2	16.2	-	-	-	-	-	-	-
$P_{Gr-Bld}$		$P_{ESS-Bld}$		$P_{PV-Bld}$		$P_{SB-Bld}$		$P_{EV-Bld}$		$P_{PV,SB-ESS}$		$P_{Bld-EV}$		$P_{Bld-SB}$		$P_{Bld-Gr}$									

The aforementioned power exchange behavior is alternated during weekends (Table II), where the schools, the cultural center and the administrative buildings have low energy needs, while the residential buildings require higher amounts of energy compared to their weekday needs. It should be noted that additional runs of the optimization model showed that the power exchanges are also highly affected by the time of the year; for example, schools during summer days and



offices/residential buildings during holiday seasons mainly sell their generated energy to the grid and the other Superblock buildings, while the cultural building buys large amounts of power during its peak load, which takes place on weekday evenings of summer months.

TABLE II: POWER EXCHANGES FOR THE SCHOOL BUILDING, ADMINISTRATIVE BUILDING, RESIDENTIAL BUILDING AND CULTURAL CENTER BUILDING, DURING THE SATURDAY OF APRIL 16TH IN 2016.

Administrative building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	2.2	2.2	2.2	2.2	2.2	2.2	1.3 0.9	2.2	2.2	4.3	4.3	4.3	4.3	4.3	4.3	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
	Power stored/sold (kW)								12.1	19.9	23.2	24.2	29.4	33	30.9	31.8	3.3 27.4								
Residential building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	7.9	7.9	7.9	3.9	3.9	3.9	7.9	7.8 51.1	7.8 47	23 32.7	27.5 30.7	2.6 24.9	27.5	8.5 19	27.5	27.5	19.7	7.9	56.9 1 6.9	31.4	31.4	31.4	7.9	7.8
	Power stored/sold (kW)	-	-	-	-	-	0.03	1.32	-	32.2	-	19.3	36.3	16.2	32.3	15.4	12.7	17.7	23.4	-	-	-	-	-	-
School building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	5.8	5.8	5.8	5.8	5.8	5.7 0.06	2.9	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	2 3.8	5.8
	Power stored/sold (kW)	-	-	-	-	-	-	-	40.5	65.5	55.5 27.2	91.6	95.2	107	100	103	31.9 60.9	53.2 34.5	67.7	52.3	-	-	44.1	-	8.7
Cultural center building	Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Power consumed (kW)	7.5	7.5	7.5	7.5	7.5	7.4 0.07	1.6 2.4 3.5	15	15	52.6	67.6	55.7 11.9	16.3 51.4	50 17.6	46.3 21.3	67.6	67.6	60.1	22.5	22.5	1.2 13.9	7.5	7.5	7.5
	Power stored/sold (kW)	-	-	-	-	-	-	-	7.4 31.9	66.4	123	42.6	102	77.2	102	102	123	39.2	13.9 16.6	20.8 23.7	82.2	-	18.6	18.2	
-																									
$P_{Gr-Bld}$		$P_{ESS-Bld}$		$P_{PV-Bld}$		$P_{SB-Bld}$		$P_{EV-Bld}$		$P_{PV,SB-ESS}$		$P_{Bld-EV}$		$P_{Bld-SB}$		$P_{Bld-Gr}$									

#### IV. CONCLUSION

In this article, we have focused on the potential of cooperation among buildings, in order to achieve increased energy self-sufficiency and to contribute to the reduction of CO<sub>2</sub> emissions. We have introduced a cooperative energy management system which coordinates a group of buildings with diverse energy consumption patterns, to exchange their excess energy produced by RES and/or stored to ESS. The application of the proposed approach results not only on the

derivation of the optimal equipment capacities but also on the determination of the optimal daily power operation plan of all buildings in the Superblock. However, such energy management schemes should go beyond from being employed only in small-scale power networks, so that they can provide an efficient way to utilize the energy generated from RES installed in entire cities. To this end, our future work focuses on the extension of the cooperative system so that entire neighboring Superblocks with diverse energy consumption patterns can cooperate and exchange their total excess energy, instead of forwarding it to the main distribution grid. Such a large-scale cooperative energy management scheme should be combined with demand response schemes in order to further reduce the energy consumption especially in peak demand periods and improve the environmental parameters that are related to the residents' quality of life.

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