A Microgrid Architecture for Integrating EV Charging System and Public Street Lighting

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Abstract— **The paper presents initial results of an on-going research and development project aimed at integrating LED-based public streetlight systems with other smart city infrastructures. The paper describes the general configuration of a microgrid unit where several systems are integrated, including power generation from renewable, energy storage, charging stations and LED-based streetlights. Possible impacts of this integration are showed considering the possible modernization and renewal of an existing public lighting system.**

Keywords—Public lighting system, Distributed Energy Resources, LED lamps, Electric Vehicles, Smart City

I. INTRODUCTION

In the years to come, the expected increase in the penetration of electric vehicles (EVs) will generate significant challenges with regard to the consequent need of charging pedestals and dedicated electrical infrastructures. EV demand will create an increase of the overall demand, requiring new dispatch and management routines to host such loads in the network. Recent estimations have found that, in countries characterized by a good penetration of EVs such as North Europe and United States, the ratio between installed charging pedestals and circulating EVs is close to 1.1, meaning that most EV owners use slow/standard charging private facilities. This ratio is reduced in more densely populated area like China or Japan where it reaches a value of about 0.8 due to the presence of public charging stations.

In order to achieve high degrees of EV penetration, a larger diffusion of fast public charging stations is required. However, connecting new pedestals to the secondary LV distribution grid is not an easy task. Considering that a typical pedestal with two sockets allowing three-phase fast charge is rated 22 kW, and that MV/LV secondary substations are usually rated 250-400 kVA, it is clear that each new pedestal requires a huge portion of the total available capacity at the LV node (comparable to the power requested by a small apartments building).

In a smart city scenario, an improvement of overall efficacy and efficiency of physical urban infrastructures, such as for example transportations, power grids, public street lighting, can be achieved creating shared platforms and interconnected networks where energy, services and materials can be exchanged [1]. The aggregation of EV charging services in urban spaces where also other energy services for smart cities are provided, can allow to obtain several advantages, including higher efficiency and flexibility, minimizing the requests for new hosting capacity, and to exploit though retrofit interventions existing feeders, such as for example the ones dedicated to public street lighting.

Thanks to the enhanced control capability of LED-based systems, innovative intelligent public lighting system have been proposed for smart city applications, in order to enhance adaptivity to traffic conditions [2], and more in general to increase efficiency and quality of light [3]. In [4] the use of smart lighting is suggested to provide energy balancing services to the grid, whereas in [5], the results in terms of efficiency and reliability following the integration of networked LED streetlights in the monitoring and control architecture of the IIT campus microgrid are presented.

If several examples of integration of public lighting systems in a smart city can be found in the literature, very few references acknowledge their possible integration with EV charging. In [6], results of the French project TeleWatt are presented, showing the feasibility of an integrated architecture where EV charging terminals, sharing the same electrical infrastructure of public lighting systems, are enabled and controlled according to arrival times of vehicles and lighting requirements. According to the authors, the TeleWatt system could easily enable the deployment in a year of about 10,000 new charging stations in the sole city of Paris. Although possibly not conservative enough, since not corroborated by detailed grid studies, these estimations give an idea of the huge potential of a similar solution.

The industrial interest on this topic is demonstrated by the appearance of new patents, for retrofitting lighting poles with EV charging sockets, and actual installations of residential on-street charging on lamp posts. Possible commercial technological solutions have been found in [7], with a system that integrates charge points in light poles or in bollards so that they can be easily integrated into residential streets without affecting the look of the street. Also in [8], an integrated solution for street use has been proposed with a LED lamp that has the double function of public lighting and charging infrastructure, with several available sizes and the capacity to charge two electric vehicles at the same time. However, these products assume that lighting and charging services are supplied by two independent power lines.

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In this paper, first findings of a R&D project aimed at integrating EV charging station with LED-based public street lighting systems in a microgrid framework is presented. The presence of possible other distributed energy resources (DERs) like renewable generation and storage is also considered. The impacts of this integration are evaluated considering the possible modernization and renewal of the existing lighting system in an actual public lighting system. One of the main rationales of this integration relies in the possibility to use the capacity already installed to guarantee EV charging hosting capacity during daylight hours or at night-time switch-off in "half-night" operation mode. The main constraints that must be taken into account consider the maximum installed power and the voltage drops along the entire street distribution. The power lines of the street lighting systems are in fact characterized by considerable lengths and considerable voltage drops even in the presence of operating currents much lower than the current ratings.

The actual system is represented using a detailed model of the lamps distribution and their daily on/off switching operations. The average availability of charging capacity is maximized through an optimization routine.

II. "EMERA" - Integrating EV Charging System and Public Street Lighting

The paper is based on results of an on-going research and development project aimed at integrating LED-based public streetlight systems with other urban infrastructures, including charging stations for e-mobility (both four and two-wheels vehicles). The project, called "EMERA", is carried out together with an Italian company specialized in the design and construction of LED lighting fixtures for outdoor, several small-medium enterprises in the ICT area and other research organizations. Thanks to the current development of ICT and IOT technology, lighting and charging infrastructures can be part of a set of aggregated services to be provided in the same urban space.

The paper describes the configuration of a microgrid unit where several systems are integrated, including power generation from renewable, energy storage, charging stations and LED-based lighting. In the proposed scenario, all components are controllable devices, including lamp post (through adaptive lighting) and EV charging pedestals. With regard to the availability or generation resources, the main hypothesis is that a small PV centralized unit, with a battery energy storage system (BESS) is installed. This unit could be for example installed using photovoltaic parking lots, built to guarantee sun shade to parked cars and rooftop surface for PV generation.

Theoretically even distributed PV and battery modules, such as the ones employed in stand-alone solar streetlights, can be integrated in the microgrid. These units are often (over)sized in order to guarantee 3-5 days of autonomous energy supply and increased levels of availability, meaning that there is a conspicuous amount of generable power that is often unused. Examples of innovative configuration permitting to centralize the use of these units in a network of streetlights have been proposed [9], in order to exploit the overall generation capacity. However, the modifications required in terms of added power electronics and power circuits appear at the moment too complex for retrofit installations.

The work presented in this paper is aimed at showing how, following renovation projects of public lighting system, a significant additional hosting capacity for EV charging can be obtained. This available capacity is due to the power reduction obtained after the substitution with LED lamps but derives also on the consideration that streetlights are switched off during the day and, partly, in the night when "half-night" circuits are switched off. Moreover, thanks to easier controllability of networked systems of lamps, the luminous flux can be curtailed in certain hours of the night when traffic conditions allow the reduction of average illuminance.

The quantity of power that can be supplied to charging station can be calculated considering the solution of an optimal problem that takes into account all available distributed energy resources (generation, storage and controllable loads) and physical limitations of the electrical circuit feeding the integrated charging/lighting.

A. Optimization problem

The optimization problem is formulated to minimize an objective function that takes into account energy costs, penalties due to the curtailment of EVs charging power, BESS wear costs for the operator of the public street lighting and EVs charging system. Equality constraints are given by the energy balance equations, whereas inequality constraints by limits on control variables and storage usage.

The objective function can be written as:

$$F = \sum_{i=1}^{n_T} \sum_{x} C_x \cdot u_{x,i} \cdot \Delta = \sum_{i=1}^{n_T} C_{TOT,i} \cdot \Delta, \quad \text{with} \tag{1}$$

$$C_{TOT,i} = C_{buy} \cdot u_{buy,i} + C_{dis} \cdot u_{dis,i} + C_{cha} \cdot u_{cha,i} + \sum_{j=1}^{n_{sock}} C_{sock,j} \cdot u_{sock,j,i}$$

and where C_{buy} is the energy cost, C_{dis} and C_{cha} represent the €/kWh battery wear cost, applied to the discharging and charging phase, respectively [10]. The cost C_{cha} was assumed to be zero in our simulations; whereas $C_{sock,j}$ is given by:

$$C_{sock,j} = p_{sell_{EV},j} + C_{pen,j} \tag{2}$$

with $p_{sell_{EV},j}$ and $C_{pen,j}$ being respectively the selling price of electricity for EVs charging and the penalties paid by the operator for a potential curtailment of EVs charging power.

The control variables are:

- $u_{buy,i}$ is the power imported at the PCC;
- $u_{dis,i}$ is the discharged power at the battery;
- $u_{cha,i}$ is the charged power at the battery;
- $u_{sock,j,i}$ is the curtailment of EVs charging power;

with the subscript *i* denoting the *i-th* time step, and *j* the *j-th* charging station socket. Since the cost of energy is usually expressed on a kWh basis, Δ is equal to 1/12 h if a 5-minutes discretization is used.

The optimization problem can be written as:

$$\min_{\boldsymbol{u}} F = \sum_{i=1}^{n_T} \sum_{x} C_x \cdot u_{x,i} \cdot \Delta \tag{3}$$

subject to $\quad g_i(u_i) = 0$

and $\quad h(u,s) \le 0$

where $\boldsymbol{u}$ is thea vector colleting all control variables at all time steps, $\boldsymbol{g}_i$ is the i-th energy balance equation, $\boldsymbol{h}$ is the set of inequality constraints.

The equality constraints representing the energy balancing equation can be written as

$$\begin{aligned} u_{buy,i} + q_{pv,i} + u_{dis,i} + \sum_{j=1}^{n_{sock}} u_{sock,j,i} = \\ = u_{cha,i} + \sum_{j=1}^{n_{sock}} q_{sock,j,i} + q_{sl} \end{aligned} \qquad \forall i \tag{4}$$

with $q_{pv,i}$, $q_{sock,j,i}$ and q_{sl} being respectively the forecasted power produced by the PV plant, the forecasted power charging demand at *j-th* socket and the forecasted streetlight power.

The inequality constraints representing hard limits on control variables $\boldsymbol{u}$, are:

$$0 \le u_{buy,i} \le u_{buy,max} \tag{5}$$

$$0 \le u_{sock,j,i} \le q_{sock,max} \tag{6}$$

In (5) the variable $u_{buy,max}$ represents the maximum power which can be exchanged at PCC, as defined in the electricity supply contract. In (6) the maximum value of the curtailable power at the charging socketis denoted with $q_{sock,max}$.

With the introduction of a binary variable $s_{cha,i}$ equal to 1 if the battery is charging and 0 if discharging, the following linear inequality constraints can be added:

$$\begin{aligned} 0 \le u_{cha,i} \le s_{cha,i} \cdot u_{cha,max} \\ 0 \le u_{dis,i} \le \left(1 - s_{cha,i}\right) \cdot u_{dis,max} \end{aligned} \tag{7}$$

Assuming constant charging and discharging efficiencies (η_{cha} and η_{dis}), at the end of any i-th time step, the energy stored can be expressed as

$$B_i = B_0 + \sum_{j=1}^{i} \left(\eta_{cha} \cdot u_{cha,j} + \frac{u_{dis,j}}{\eta_{dis}} \right) \tag{8}$$

where B_0 is the initial charge. Consequently, the inequality constraints $B_{min} \le B_i \le B_{max}$ are linear expressions of $\boldsymbol{u}$.

Due to the mixed integer and continuous nature of the variable a MILP solver [11] has been adopted to obtain the overall optimization solution.

Note that since some variables are forecasted, control variables, obtained by the solution of the optimization problem, have to be considered as an assessed control action. When applied, in the reality , controls may yield an imbalance in the equality constraints (4). In this case, the PCC assumes the role of a "slack bus" absorbing the differences among the expected variables and the actual ones. If the requested power at the PCC exceeds the maximum power $u_{buy,max}$ defined in the contract, a load curtailment at a predefined socket will be applied.

III. Test Results

The following tests are aimed at showing how new EV charging hosting capacity can be obtained through the modernization of old public lighting systems and the substitution of sodium-vapor lamps with LED. The following test cases are based on the structure of an existent public lighting distribution system in the city of Bari. The system used for test is represented in Fig. 1 showing the location of the main switchboard, which will then represent the point of common coupling (PCC) of the integrated charging/lighting microgrid, and the position of each lamp post. In this same figure, it is possible to identify which circuits are operated according to "full-night" and "half-night" modes. Rated power of lighting fixtures refers to the actual installed lamps.

Fig. 1. Scheme of the public lighting system under study

In Table I, the main characteristics of the lighting system under study are synthetized. The system is characterized by a total absorbed power of 30.8 kW including losses. Each sodium-vapor lamp is usually rated from 150 to 400 W. After the substitution with LED lamps, the same level of illuminance can be obtained employing about 7.5 kW of active power, including losses, and lamps rated about 100 W or less. Considering that actual available capacity of this electrical circuit is 37.2 kW, it is clear how, if lamps were substituted, a relevant hosting capacity to be employed for EV charging would be freed. Another advantage of employing networked systems of LED lamps, is that on/off cycles and timings can be controlled remotely, with each lamp allowed to receive a specific switching command. This feature represents of course a significant improvement with respect to older lighting systems where "half-night" operation was achieved by switching on and off the supply circuit at switchboard level.

TABLE I. Lamps Installed in the Public Lighting System

Type of lamp installed	Number of lamps		Active power [kW]	
	"full-night"	**"half-night"**	**"full-night"**	**"half-night"**
Sodium-vapor lamps (before)	43	32	14.9	11.8
LED lamps (after)	43	32	4.1	3.1

In Fig. 1, the possible location of three solar car parks with EV charging stations is also shown. Conservatively it has been assumed that each PV canopy covers two parking bays and has a generation capacity of 2 kW_p. Two charging stations are assumed to have two T3A (3.7 kW) sockets, whereas only one station has a T3A (3.7 kW) and a T2 (22 kW) socket. EV charging stations are installed very close to the PCC so that their influence on power losses and voltage drop, at this stage of development, can be neglected.

A. *Assessment of theoretic maximum hosting capacity*

This test case is aimed to assess the maximum hosting capacity obtainable in a day of operation, starting from 12PM to the 12PM of the following day. This interval was chosen so that a complete cycle of on/off operation of the lighting system is considered. Hosting capacity is obtained minimizing the previously defined cost function that takes into account also revenues from EV charging and possible penalties due to charge curtailments. At this stage of development voltage drop constraints were not taken into account, however it is possible to imagine that a detailed representation of LV components can be adopted for optimal load curtailment in the presence of wider networks and higher penetration of charging stations [12].

For this test case, it was assumed that each socket is continuously connected to an EV requiring charge at the maximum rated power. Although unrealistic, this assumption permits to evaluate the theoretical maximum daily capacity. The optimal problem presented in the previous paragraph, was solved considering the actual on/off switch times of a mid-season day and the registration of PV production from a real plant, suitable scaled to represent the response of the simulated 6 kW_p generator.

Figure 2, represents how EV charging capacity can be assigned to each socket along the day. Depending on the availability of renewable generation, all sockets can be powered during the central day hours, when streetlights are off. During night operation, some sockets should be disabled in order to avoid power curtailment. In this test, a scheduling policy to decide which socket should be enabled and which not was not modelled. However, typical policy schemes such as *first come first served*, *earliest deadline first* or *lowest energy requirement first*, as proposed in [13], can be easily implemented.

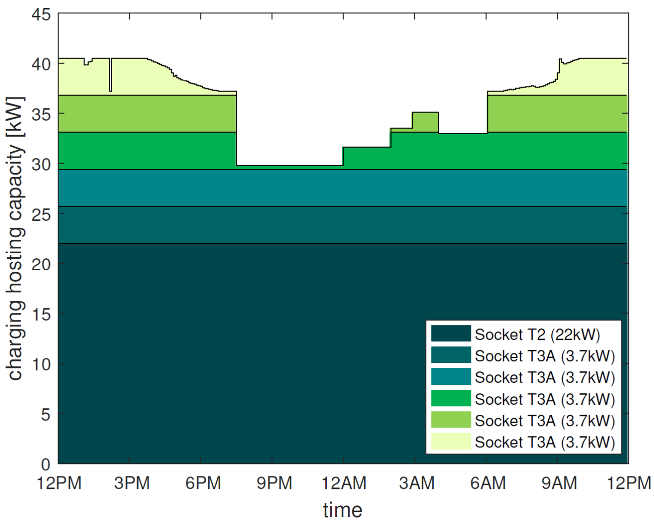

Fig. 2. Available charging hosting capacity (no scheduling policy)

A possible modification to the charging scheduling could be based on deactivating or downgrading the fast charging socket during night hours. This condition, although theoretically non-optimal, in practice can allow to increase the number of charged vehicles in the nighttime, when vehicles stay parked for longer time and fast charging availability is not critical. A different solution of the same optimal problem solved before is given in Fig. 3, making the assumption of downgrading the fast charge socket. It can be noticed how, even when "half-time" lamps are switched on, the system is able to provide full capacity to each socket. Another possible approach is to develop a scheduling policy that prioritizes slow charge in the nighttime.

In the previous cases, the presence of a BESS was also assumed, but with no influence on results, since the entire system capacity plus PV generation was used during the day hours to supply continuously energy to the EVs, and BESS was consequently never charged. This result is due to the assumption of continuous charge request and to the limited amount of available PV generation. Next test results, where more realistic charging profiles are simulated, will show how stored energy can be used to provide hosting capacity during the night.

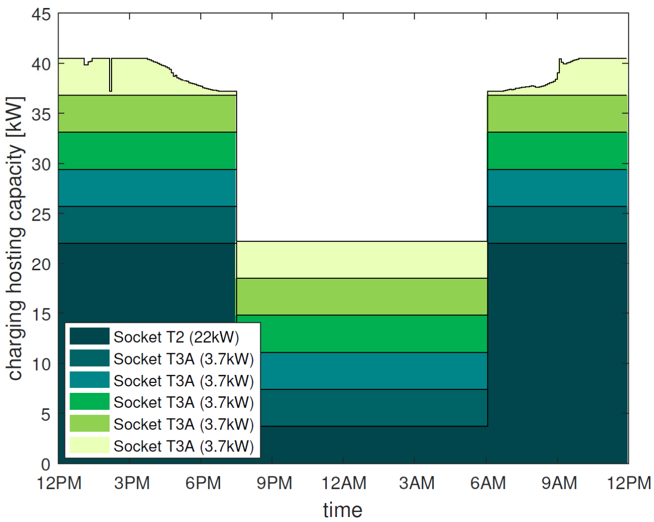

Fig. 3. Available charging hosting capacity (fast charge night disactivation)

B. *Optimization of a daily schedule*

In Fig. 4 and Fig. 5 a realistic EV charging demand profile has been assumed. The T2 (22 kW) socket is used for fast charging during daylight time when photovoltaic source is available whereas five T3A (3.7 kW) sockets are mostly utilized during the night for slow charging. In Fig. 4, the maximum power at the PCC has been assumed equal to 37.2 kW whereas in Fig. 5 it assumes a lower value equal to 10 kW.

The case represented in Fig. 5 was introduced to show the potentials of the BESS to reduce the maximum power in the supply contract. It can be observed from Fig. 4 that the battery is never discharged since it is more convenient to import power from the PCC (see the red bars). Differently, Fig. 5 shows two periods where the BESS is discharged (see the yellow bars). In Fig. 5 the optimization procedure assesses a control action based on the full exploitation of the photovoltaic source and the purchase of a limited amount of energy from the PCC in order to ensure fast charging later on thanks to storage. This was due to the limitations assumed on the maximum power available at the PCC.

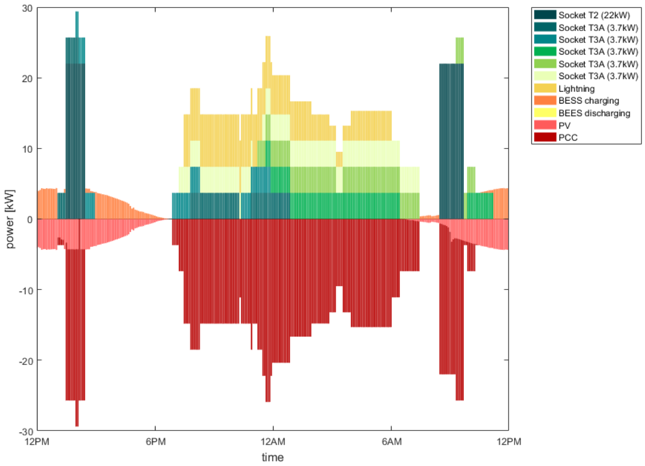

Fig. 4. Optimization assuming maximum power at PCC (37.2 kW)

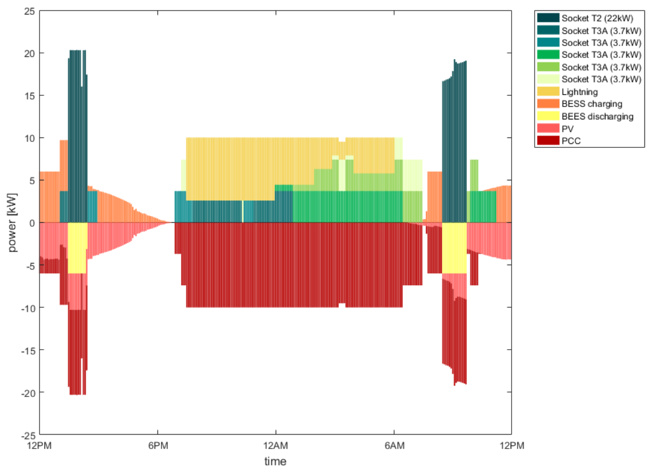

Fig. 5. Optimization assuming maximum power at PCC (10 kW)

IV. Conclusions

First results in the execution of a R&D project for the integration of LED-based public lighting system with EV charging station have been presented. The potential outcomes of integrating these two infrastructure within a microgrid framework were assessed in the case of a renewal project for the substitution of old sodium-vapor lamps with LED. The results have shown how a significant additional EV charging hosting capacity can be guaranteed thanks to the lower consumption of LED lamps, the control of luminous flux and the optimal dispatch of other available energy resources.

Together with the development of suitable EV charge scheduling algorithms, future efforts will be spent in including physical network constraints on currents and voltages into the formulation of an optimal control problem aimed to allocate optimally the EV charging capacity. Furthermore, it is possible to imagine the adoption of a two levels hierarchical control architecture where a closed-loop controller, following events such as the arrival or departure of an EV, and having checked the respect of voltage and power constraints, readapts in real time the optimal scheduling evaluated from the optimal control routine.

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