Economic and Environmental Impact of Electric Vehicles Trends on Jointly-Acting Renewable Self-Consumers Groups

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***Abstract*—Extended forms of self-consumption, including jointly-acting renewable self-consumers and renewable energy communities, are extremely promising instruments for the dissemination of renewable energies and the achievement of European targets regarding sustainability and reduction of greenhouse emissions. At the same time, electrification in the transportation sector is developing faster and faster, with great success also among private users. In this paper, we will consider an apartment building, the inhabitants of which, thanks to the installation of a photovoltaic and storage system, acts as a group of jointly-acting renewable self consumers, with the aim of gaining advantages in economic and environmental terms. In particular, the impact of the foreseen increase of electric vehicles owned by inhabitants in terms of costs and CO_2 emissions is investigated. A range of possible scenarios will be considered, including different sizing and management criteria of the photovoltaic and storage system, with and without the establishment of a jointly-acting renewable self consumers group.**

***Index Terms*—renewable energy communities; jointly-acting renewable self-consumers; energy transition; CO_2 emissions; electric vehicles**

I. Introduction

The energy transition and the decarbonisation process are pushing towards less pollutant energy sources, which will enable the reaching of the targets set by the European Union for the coming years as quickly as possible. In this context, the decarbonisation of the energy sectors, being the main emitters of greenhouse gases, is a matter of the utmost relevance [1].

Among the various strategies for reducing pollutants, the electrification of energy sectors is potentially the most effective due to the clear improvements in efficiency and overall emissions, unitedly with the many factors common to several energy-intensive sectors [2]. However, the electrification process cannot act alone and needs to be supported by renewable energy sources (RES) for power generation carrying a lower environmental impact with respect to traditional fossil fuels.

Among renewable energy sources, photovoltaic (PV) generation is definitely the preferred one in both residential and commercial/industrial sectors due to its strong versatility, quick installation and low payback time [3], [4]. A PV system is typically installed on the roof of a household to power day-to-day consumption and thus reduce the energy drawn from the grid. However, especially in residential contexts, consumption is mainly distributed in the early and late hours of the day due to the presence of occupants. In order to increase self-consumed energy, a battery energy storage system (BESS) is often included in the system to store the excess of PV energy instead of feeding it to the main grid. Clearly, the sizing of PV-BESS plants is highly dependent on the available surface, energy consumption profiles and the initial cost that the users are willing to afford, as seen in [5].

The deployment of RES plants installations is supported by recent European directives (Articles 21 and 22 of RED II [6]) that allow the establishment of extended forms of self consumption, namely renewable energy communities (RECs) and groups of jointly-acting renewable self-consumers (JARSCs), with the aim of sharing self-produced energy among community members to pursue energetic, economic, environmental and social benefits. The establishment of these new aggregations is encouraged by an economic incentive proportional to the shared energy.

In an apartment building context, a PV-BESS system can be highly profitable for the energy supply of common loads such as lifts, lighting and centralised heat pumps. Moreover, in recent years, there has been strong growth in the market for electric cars due to reduced purchase costs, increased range and increasingly widespread charging infrastructure [7]. For this reason, the use of charging wallboxes at the residential level is also growing strongly, thus enabling a faster pace in the electrification of the transport sector.

The literature includes several studies on the analysis of JARSCs and RECs from different aspects, such as legislative [8], [9], social [10], [11], techno-economic [12], [13] and environmental [5]. Furthermore, the integration of JARSCs and RECs with electric mobility has also received much interest in recent years [14], [15]. For example, in [16] the energy and

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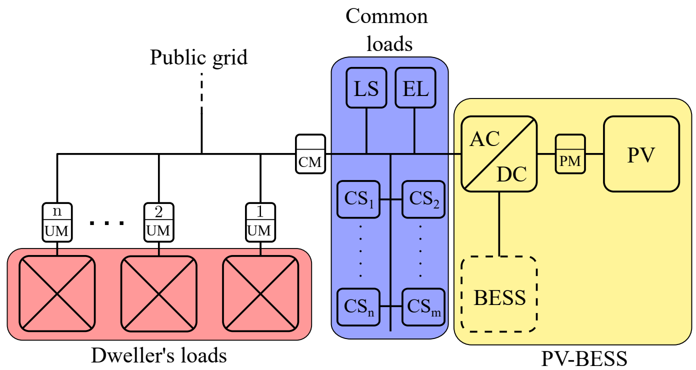

Fig. 1. The JARSC electrical system under consideration. Common loads consists of lighting system (LS), elevator (EL), and the EVs charging stations (CS).

environmental impact for an apartment block JARSCs group is analysed by evaluating different scenarios that consider both thermal and electrical consumption, including the use of EVs. However, it does not consider a variation in the capacity of the cars and/or their charging power during the years of operation of the community. In [17], the impact of EV consumption is studied for the optimal sizing of JARSC through stochastic optimisation. In the study, three different electric mobility scenarios are analysed, in each of which vehicles are added and their impact on optimal sizing is evaluated. However, the case study relates to a university campus where employees' vehicles are charged mainly during the daytime, easing the pursue of high self-consumption considerably. Also in this case, the vehicles are not varied over the lifetime of the energy community.

This paper focuses on the impact over the years of the variation of the number and of the electrical characteristics of the EVs of the inhabitants of an apartment block configured as a JARSCs group. The results of different scenarios and possible sizing are analyzed from an energetic, economic and environmental point of view. Optimal sizing for the different scenarios are obtained from the methods presented in [5], which is based on minimizing a combination of payback time (PBT) and equivalent CO_2 emissions due to energy absorbed from the grid.

The paper is structured as follow: Section II reports the description of the system and its main parameters and specifications. Section III reports the methods used for the generation of the EVs charging profiles based on real EV trip data and statistical analysis. The definition of the simulation scenarios for different PV-BESS sizing are detailed in Section IV while final discussion and results are drawn in Section V. Lastly, final conclusions rising from the study are reported in Section VI.

II. System Description and Specifications

The electrical scheme of the JARSCs group considered in this work is shown in Fig. 1, which is assumed to be located in Milan. It consists of twelve flats, each with a different load profile and with its own energy meter (UM). A photovoltaic system is installed on the roof of the building and a production meter measures the PV energy produced. To improve self-consumption, a BESS system with integrated DC/AC converter is installed. The common meter (CM) is used to measure the energy exchange of the common loads and the PV-BESS system. The energy management is controlled by a rule-based energy management system (EMS), which determines the charging and discharging power of the battery based on instantaneous consumption and production measurements, considering the BESS state of charge (SOC) and its limits.

The PV-BESS system consists of a number of PV modules connected in series and in parallel to meet the constraints of the inverter and the roof area under consideration. The nominal power of a single PV module is 400 W with an efficiency of 22.6%. Profiles of solar irradiance and ambient temperature with hourly time granularity were extracted from an online database [18] in order to generate the PV annual power profile, as shown in [19]. The BESS system consists of a number of 2.5 kWh lithium-ion modules, installed in parallel to reach the desired total capacity.

In order to obtain the twelve flat load profiles, a residential load profile generator was used [20], which is based on behavioral models of the user's habits. The generator simulates the user's daily behaviour and then determines possible household activities from which a consumption profile can then be obtained. The desired twelve different profiles were then associated with each flat, resulting in different annual consumption and different contractual power.

The common consumption of a condominium is mainly due to the use of devices and systems that each user use on a daily basis, the costs of which are shared equally by the inhabitants. In this case, common loads consist of a lighting system for the common parts, a lift and the community users' wallboxes. The latter will be increased during the operational life of the JARSC in order to evaluate the economic and environmental effects of increased penetration of EVs. The power profiles related to these systems were determined based on relations with the inhabitants' work activities and lifestyle, as described in detail in [5]. Additionally, common loads include the charging stations (CS) depicted in Fig. 1. The corresponding load profiles are discussed in detail in Section III.

In order to analyse the economic and environmental impact of the vehicles on the community, it is necessary to define price profiles for the purchase and sale of energy as well as a factor that determines the equivalent amount of CO_2 emitted due to the energy drawn from the grid.

Regarding costs, the excess energy produced is sold to the electricity grid through a minimum selling price (PMG - Prezzo minimo garantito) which is fixed and equal to 4 c€/kWh. For the purchase price of the energy, a two-hourly tariff has been assumed. In particular, in the 8 a.m. - 7 p.m. time slot, electricity is purchased at the cost of 30.5 c€/kWh while, from 7 p.m. to 8 a.m. at 28.5 c€/kWh. Addiontal costs to be considered are the fixed costs and system charges, which amount on average to 5.86 c€/kWh, and, finally, VAT, equal to 10% for the 12 user's meters and to 22% for the non-residential meter (CM). Addtionally, if a REC or JARSC is established, an incentive is provided on the basis of shared energy. The latter is defined as the hourly minimum between the energy produced and fed into the grid by the renewable generator and the energy consumed by the users forming the REC or JARSC community. Shared energy is remunerated with an incentive of 10 c€/kWh for JARSCs (11 c€/kWh for RECs) and a compensation for avoided grid losses and distribution fees of about 1.15 c€/kWh. Additional data required for the economic analysis have been sourced from [5]. Although there are different types of energy exchange within a JARSC, our work is based exclusively on virtual exchange, the only allowed method in Italy. Potentially, however, it is also possible to carry out a physical exchange [21]–[23] but this is currently not permitted in Italy.

Concerning the environmental cost of electricity, the carbon intensity for the northern part of Italy was calculated on the basis of the various energy sources included in the electric system. These data are available on an hourly basis from the ENTSO-E database. Each type of non-renewable (coal, fuel oil, natural gas, etc.) and renewable (PV, hydro, wind) production is characterised by a different emission factor that determines their impact on the environment. This results in a value of equivalent gCO_2/kWh for each hour of the day, which represents the amount of CO_2 that is emitted for each unit of energy absorbed from the grid depending on the current energy mix. The combined minimisation of equivalent CO_2 emissions and PBT are the basis of the sizing method proposed in [5], which is used in this work to determine the installed PV plant power and BESS capacity.

III. EVs LOAD PROFILE

The charging profile of the individual EV depends on its maximum charging power and battery capacity. Additionally, the vehicle arrives at the charging station with a residual energy strongly influenced by several factors, such as the covered distance, driving style, speed and battery energy at the start of the journey. In this study, a dataset of 265 real trips conducted by the staff of the University of Trieste using a rented EV (Nissan Leaf 40 kWh) was used. Based on the trips, it was possible to measure the distance travelled and the vehicle's electric consumption for different trip types, urban ($\leq$25 km) and extra-urban (>25 km). The breakdown of the trips made it possible to generate two different distributions allowing the development of a probabilistic model for the travelled distance. The distributions corresponding to urban and extra-urban trips are reported in Figure 2 and 3, respectively. Starting from these data, a fitting process was performed using the Kernel distribution. The characteristic parameters of the two distributions, the kernel function and the bandwidth (BW), are shown in the two corresponding figures. From the same data, thanks to an embedded datalogger, it was also possible to obtain the average consumption of the two types of journey. In particular, for the urban trip the vehicle consumes on average 0.2 kWh/km, while for the extra-urban trip the average consumption is equal to 0.24 kWh/km.

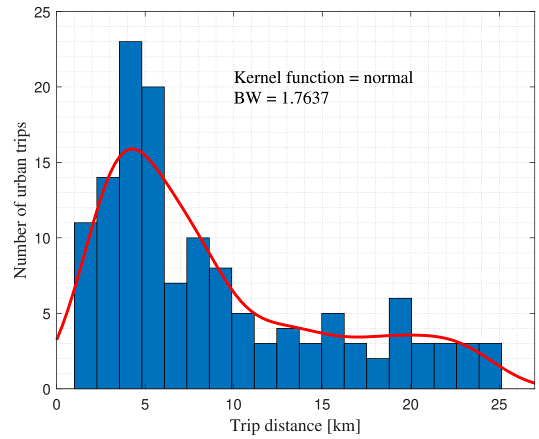

Fig. 2. Distance distribution and fitted distribution function for urban trips.

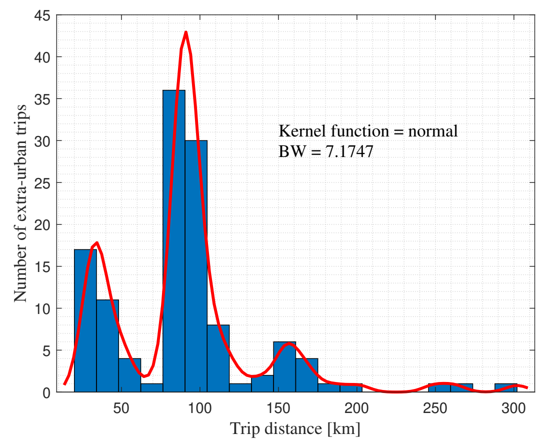

Fig. 3. Distance distribution and fitted distribution function for extra-urban trips.

The EV charging profile of a typical JARSC user can hence be modelled on this basis, assuming that each user charges the car every time it is recovered from a trip. The user is assumed to travel to work with the EV five days a week, running an urban-type trip, while on Saturdays and Sundays the user is assumed to stay home or to take a daily extra-urban trip. On all days, if a trip is scheduled, the leaving hour is randomly selected within a time range between 5 a.m. and 9 a.m., while returning hours is randomly picked between 5 p.m. and 9 p.m.. Based on the two previously obtained probability distributions, the distance of the trip is randomly selected, resulting in a different arrival SOC (SOC_{arr}) for each day. The residual SOC is calculated through:

$$SOC_{arr} = SOC_{dep} - D \cdot C \cdot \frac{100}{E_B} \quad (1)$$

where SOC_{dep} is the state of charge of the vehicle at the departure, D is the trip distance, C is the trip average consumption and E_B is the EV total battery capacity. Once the vehicle has returned to the JARSC charging station, it is connected to the wallbox and charging begins. The single charging power profile was extracted from the Nissan Leaf charging dataset with a 5-minute sampling time. In order to preserve battery life, the manufacturer limited the charging power to the maximum power for a SOC between the minimum and 80 per cent while for higher SOC the power is decreased exponentially until the vehicle is fully charged.

By combining the trip model with the recharging power profile, it was therefore possible to obtain a power profile on an hourly basis that depends both on the trip type and on the specific EV characteristics (capacity and maximum recharging power). According to this method, different profiles were obtained to associate with the energy flows of the community for the different scenarios discussed in the following.

IV. Definition of Simulation Scenarios

For sizing and simulation purposes, the following scenarios are considered over a 20-years horizon:

- Scenario 0: in this scenario, seen as a reference for economic and environmental analysis, it is assumed that the loads are completely fed by the grid. No PV-BESS system is installed;
- Scenario 1: in this scenario, a PV-BESS system is installed but no JARSC group is established. The EMS is used to store the energy generated by the PV system which cannot be consumed in real time by the common loads, which is used later to feed the common loads when PV generation is insufficient. Energy is sold only when PV generation is larger than common loads absorption and the BESS is fully charged, and bought only when PV generation is smaller than common loads absorption and the BESS is fully discharged;
- Scenario 2: technically equivalent to Scenario 1, but a JARSC group is established, giving access to the related economic incentives. User's meters data are not available in real time;
- Scenario 3: in this scenario, a PV-BESS system is installed and a JARSC group is established and each user's meter data are available in real time. The EMS is used to store the energy generated by the PV system which cannot be consumed in real time by the common loads or shared with the other loads, which is used later to feed the common loads and to be shared with other loads when PV generation is insufficient. Energy is sold only when PV generation is larger than common loads and other loads absorption and the BESS is fully charged, and bought only when PV generation is smaller than common loads and other loads absorption and the BESS is fully discharged.

As mentioned, the procedure shown in [5] to find the optimal sizing of the PV-BESS system to minimize PBT and CO_2 emissions has been adopted in this work. The sizing of the system is conducted with the aforementioned irradiance and temperature profiles, household consumption profiles and common loads, starting with only two EVs with 40 kWh battery capacity and 7 kW maximum charging power. EV charging power profiles are obtained as described in Section III. Under these assumptions, three different optimal sizing are found (Table I), corresponding to the last three aforementioned scenarios. For each sizing, the number of series-connected PV modules (N_{ser}), the number parallel-connected strings (N_{str}) and the number of BESS modules (N_{mod}) are defined. For convenience, the total BESS energy capacity E_{BESS} [kWh] and the nominal PV power at STC (Standard Test Conditions) P_{PV} are also shown in Table I.

TABLE I
Different sizing for the PV-BESS system.

	PV			BESS	
	N_{ser}	N_{str}	P_{PV}	N_{mod}	E_{BESS}
SZ_1	3	14	16.8	18	45
SZ_2	3	14	16.8	15	37.5
SZ_3	3	18	21.6	9	22.5

In each of the considered scenario, the number of EVs is increased every five years, and their battery capacity is varied, over the considered 20-years horizon (2022-2042), according to Table II, where it is assumed that the new cars added each five years are added (and do not substitute) to the older ones. The charging stations (Wallbox Pulsar [24]) are assumed to be bought by the households and their costs are considered in the JARSC group total cash flows. In particular, the cost for the 7 kW version is 849 € while for the 22 kW variant the cost is 899 €. The change in charging power and battery capacity over the years has been calculated based on estimated trends for the coming years, as described in [4], [25].

TABLE II
EV specifications variation over the PV-BESS lifetime

Year		2022	2027	2032	2037
EV	n	2	2	2	2
	P [kW]	7	7	22	22
	C [kWh]	40	62	90	90
CS [kW]		2x7	2x7	2x22	2x22

V. Results and discussion

The complete 20-years horizon has been simulated for each scenario and for each sizing with only the two initial EVs, resulting in 9 combinations plus the reference case (Scenario 0). Additionally, all simulations have been repeated with progressively increasing EV penetration, as discussed in the previous section. Successively, the economic and environmental indicators have been evaluated for combination of the considered sizing and scenarios. The considered economic indicators are: net present values (NPV) at 20 years, internal rate of return (IRR), and payback time (PBT). The considered environmental indicator is the total equivalent CO_2 emission. Tables III,IV, V and VI show the values of NPV, IRR, PBT and total CO_2 emissions, respectively, for all sizing and scenarios. Each scenario where EVs are increased over the years (EV_+) is compared with the case where no EV variation is performed and only the two initial EVs are considered (EV_0).

Regarding the economic aspect, it is easy to see how the growth of EVs brings economic benefits in specific scenarios to the entire community. As it can be seen in S_1 and S_2, the NPV increases for all sizing when the EV growth is considered. In fact, the NPV variation between EV_0 and EV_+ is caused by the increase in the self-consumed energy downstream of the common meter (CM), leading to economic savings year after year. However, the NPV values in scenario S_2 are higher than in scenario S_1 because of the higher cash flow inputs due to the economic incentive obtained for energy shared with the apartments through the establishment of the JARSC community. Regarding the NPV variation in the EV_+ case, the NPV increment in S_1 is 24.3%, 20.9% and 14.5% and in S_2, 13%, 10.88% and 6.67% for SZ_1, SZ_2 and SZ_3, respectively.

However, different considerations must be made for the S_3 scenario. In fact, as can be seen, the different EMS priorities certainly increases the energy shared among the community, which, however, is not as profitable as increasing the self-consumed energy from common loads.

The above considerations are reflected in the internal rate of return. In fact, the IRRs calculated in Table IV closely follow the NPV trends shown in Table III. As can be seen, the IRR in the different situations varies between a minimum of 7.58% to a maximum of 10.15% with an average IRR of 8.65%.

With regard to PBT, on the other hand, it is shown that the variation of EVs over the years is not particularly significant. In fact, in all scenarios, the change in PBT considering the EVs variation is negligible compared to the case where EVs are not changed. This therefore ensures that even if sizing is done without considering future increases in EVs, the payback time is not particularly affected in all three scenarios analysed. Nevertheless, it should be noted that the main purpose of RECs and JARSCs is not the maximisation of economic profit but rather the reduction of costs and the encouragement of the installation of new renewable energy plants, with all the consequent environmental benefits.

Table VI shows the total equivalent tons of CO_2 emissions calculated based on the previously defined carbon intensity profiles. As a first observation, it can be seen that in scenarios S_1 and S_2, the values of CO_2 emitted are exactly the same, as the difference between the two scenarios lies in the establishment or not of the JARSC group, leading to differences only in the economic indicators. However, among these two scenarios, it can be seen that the increase in EVs undoubtedly leads to an increase in the CO_2 emitted during the considered years, increasing it by 26% on average in all sizing. This is, however, unavoidable, as the increase in load to do the increased number of EVs requires more energy from the grid. Only a different (and periodically updated) PV-BESS sizing can limit this phenomenon. The same considerations can be drawn for the S_3 scenario, where the increase in EVs leads to an increase in CO_2 emissions over the years by 32% on average in all sizing. This effect is more pronounced in this scenario, as more energy is shared during the day, leaving less energy to be used for EV charging during the night. However, the different management of the BESS system in the S_3 scenario allows less bought energy from the grid and

TABLE III
NPV [€] over 20 years of PV-BESS system operation for different sizing and scenarios.

	S_1		S_2		S_3	
	EV_0	EV_+	EV_0	EV_+	EV_0	EV_+
SZ_1	32 017	39 811	43 097	48 700	37 530	37 311
SZ_2	32 624	39 454	43 882	48 658	37 465	36 483
SZ_3	34 061	39 007	47 770	50 957	39 679	37 816

TABLE IV
IRR [%] over 20 years of PV-BESS system operation for different sizing and scenarios.

	S_1		S_2		S_3	
	EV_0	EV_+	EV_0	EV_+	EV_0	EV_+
SZ_1	7.58	8.20	8.50	8.95	8.03	8.01
SZ_2	7.92	8.54	8.97	9.40	8.37	8.28
SZ_3	8.40	8.90	9.83	10.15	8.98	8.80

TABLE V
PBT [years] of PV-BESS system for different sizing and scenarios.

	S_1		S_2		S_3	
	EV_0	EV_+	EV_0	EV_+	EV_0	EV_+
SZ_1	10.68	10.71	9.62	9.61	9.95	10.26
SZ_2	10.08	9.98	9.32	9.35	9.71	9.86
SZ_3	9.69	9.68	8.81	8.88	9.31	9.49

TABLE VI
Total equivalent CO_2 emitted [tons] over 20 years of PV-BESS system operation for different sizing and scenarios.

S_0	
EV_0	EV_+
228.94	276.54

	S_1, S_2		S_3	
	EV_0	EV_+	EV_0	EV_+
SZ_1	165.22	208.19	136.9	184.27
SZ_2	166.66	209.96	141.4	189.03
SZ_3	164.4	208.52	145.58	192.95

thus reduces the CO_2 emissions compared to all cases of the corresponding S_1 and S_2 scenarios, leading to an average reduction of 14.3% in the EV_0 cases and 9.5% in the EV_+ cases. With respect to Scenario 0, it can be seen that the total CO_2 emissions are considerably lower in all scenarios due to the PV-BESS presence.

VI. Conclusions

Electric mobility is a strongly growing sector, and the spread of EVs is of crucial importance for the decarbonisation of the energy sectors alongside the spread of renewable energy. In this paper, a condominium operating as a jointly acting renewable self-consumers (JARSC) community is considered, and the impact of the increase of EVs penetration on the JARSC group economic and environmental indicators is evaluated. Different scenarios are considered, and different sizing for the PV-BESS system are evaluated, with the aim of minimising PBT and total CO_2 emitted during the system's operating life. The presented results highlight that the establishment of a JARSC group is effective in increasing NPV, IRR and reducing PBT and CO_2 emissions, regardless of the EMS control priorities. The foreseen increase in EVs penetration requires additional expenses for chargers and energy consumption, but also allows for increased self-consumption, so that no negative effects on PBT are recognized. The two considered EMS control priorities, on the other hand, have a more significant impact. The first considered EMS control logic, applied in scenarios 1 and 2, prioritizes BESS charging over energy sharing. This is effective in reaching higher NPV and IRR, as self-consumption is more remunerative than shared energy, and leads to improved economic indicators with increased EVs penetration. On the contrary, the second considered EMS control logic, applied in scenario 3, prioritizes energy sharing over BESS charging. This is effective in reducing CO_2 emissions, as shared energy does not suffer the efficiency penalty related to battery charging and discharging, but not optimal in reaching higher NPV and IRR. As a consequence, economic indicators suffer from a marginal reduction when EVs penetration is increased in the third scenario, which, however, is the most favourable in terms of CO_2 emissions reduction.

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