Assessing the Optimal Scenario of Collective Self-Consumption Groups in Net Zero Condominiums

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Abstract. The energy transition promoted in European countries to improve the sustainability of the energy sector brings together citizens to generate, share and sell energy produced by locally owned renewable plants. Energy communities (ECs) and collective self-consumption (CSGs) groups are strategic power-sharing models to drive this democratization process in a flexible way. However, these two models face challenges such as regulatory barriers, technical limitations, and social acceptance. In addition, the optimal sizing in terms of consumption and production to locally balance the EC load and generate the best obtainable value for all stakeholders represents another pivotal challenge. In this framework, the study proposes a methodology to assess multiple sizing scenarios of the generation and storage system in condominiums, applying an innovative multi-criteria techno-economic approach that allows to analyze the potential benefits that can be obtained by simulating. A case study of a collective self-consumption group located in a smart building in Italy is developed to assess the relevance of the methodology. The investment case supported by a third-party investor is evaluated and analyzed.

Keywords: Energy Transition · Collective Self-Consumption Groups · Scenarios · Investment Evaluation

1 Introduction

Energy transition represents one of the main objectives of the European Green Deal strategy [1] to achieve climate neutrality by 2050. The Mid-century zero emissions strategy for the EU aims to create an energy sector based mainly on renewable sources (decarbonizing the European energy system) to guarantee a secure and affordable energy supply and to improve energy efficiency, especially of the existing building stock.

As a matter of fact, the building sector is responsible for approximately 40% of global Greenhouse Gases (GHG) emissions in the environment [2], More precisely, GHG

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emissions from the building sector represented 35% of energy-related EU emissions in 2020 [3]. Similar percentages are recorded in Italy, where the poor energy performance of a significant asset [4] requires a deep renovation to reduce buildings energy consumption [5, 6], at different urban scales, in line with the circular economy perspective [7, 8].

However, international geoeconomical and geopolitical events, which are among the main causes of the increase in energy consumption from coal and oil in the most recent years, might threaten the "green" transition. This represents one of the reasons why the scientific debate on the energy transition [9–11] should consider the right to access to electricity and, therefore, to the primary services that energy makes possible [12, 13]. In this sense, the EU's legal energy policy framework and instruments such as EC may be able to face and alleviate energy poverty.

Energy communities (ECs), introduced by the RED II Directive [14], are emerging as an effective solution to mitigate energy poverty, to combat climate change and drive the transition to renewable energy sources. In line with the Integrated European Market Directive (IEM, 2019/944 [15]), ECs comprise individuals, households, businesses, or public institutions that collectively generate, consume, share, and manage locally produced energy, within a sustainable development perspective [16]. These collaborative groups or organizations aim to create a sustainable electricity system through active citizen participation [17], thus fostering democracy and resilience of local communities and places [18]. ECs developed at different locations and scales (from small-scale solutions to large-scale urban schemes) are supported by specific technologies, financing, and legal arrangements [19, 20].

However, ECs face several practical challenges, such as technical limitations, as well as regulatory barriers and social acceptance. In this study the authors propose a methodology aimed at obtaining optimal sizing of ECs, in terms of consumption and production, and the greatest benefits for stakeholders.

In Italy, where incentive policies (tax deductions) constitute the main strategic government policy to improve energy efficiency in the existing building stock, two models have been defined to promote energy communities: Renewable Energy Communities (RECs) and Collective Self-Consumption Groups (CSGs) [21, 22]. Given that both aim to increase the share of renewable energy in the Italian energy sector, there are significant differences between the two, in terms of scale of implementation (1), management model (2) and incentive framework (3):

1) RECs [23] usually involve multiple stakeholders to implement and manage large renewable energy projects; CSGs focus on single buildings like condominiums. It means that the distribution network also differ: while RECs are supported by a certain number of users dispersed over the territory, CSGs are instead based on a scheme that concentrates the consumption points within a building or a group of adjacent buildings. Figure 1, show a virtual model for a CSG, which allows the connection of the condominium network to the public distribution network using multiple fiscal energy meters, enabling separate electricity supply contracts for general services and individual housing units [24].
2) RECs require the establishment of a legal entity by virtue of the different spatial distribution and heterogeneous nature of participants; CSGs are considered a "management entity" associated with single buildings.

3) Both models are supported by incentives that encourage energy sharing among users, but the amount granted differs for CSGs and RECs.

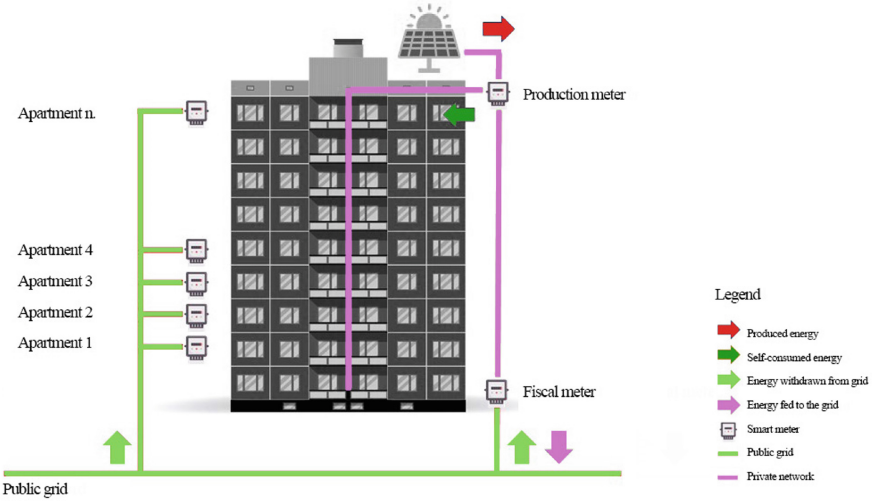

Fig. 1. A "virtual" configuration model chosen by Italian authorities for a CSG, where each user retains individual rights and obligations as an end customer.

The manuscript, that derives from previous studies conducted by the authors [25, 26], proposes a strategy for the optimal sizing and financial feasibility of collective self-consumption groups. This study is developed within the Ecosystem of Innovation for Next Generation Sardinia (e.INS) partnership, spoke 7 (Low emissions technologies for the efficient energy system), work package 4 with the objective of developing methodologies capable of bridging the complexity that can characterize the prototyping, implementation, and management of an energy community within a smart city district. Additional contributions to this study have been achieved as well within the Smart Communities for Resilient Energy Transition Project (SCoRET). An innovative multi-criteria techno-economic approach allows to explore the potential social and economic benefits for members at energy price variations. More precisely, Python is used to develop a simulation tool to assess different sizing alternatives in different scenario configuration. The possibility to easily simulate a significant number of scenarios that differ in the configuration parameters and the possibility to evaluate the generated scenarios under different perspectives that can consider social, economic and/or environmental factors represent a significant result that advance the current state of the art.

Within this framework, the manuscript is organized as follows: Sect. 2 describes the methodology employed; Sect. 3 focuses on the case study; Sect. 4 discusses the results of the methodology employed and their relevance in the disciplinary scientific debate.

2 Methodology

The study's methodology is described in this section. The authors developed a simulation tool for CSG groups leveraging Python language, particularly, NumPy and Pandas libraries have been used for data management. Using this tool, several techno-economic possibilities for combinations of solar power generation and storage system sizes can be evaluated. The main inputs of the software are the list of energy prices, demand profiles, lists of plant sizing under study, and the cost and incentive structure. The results of the simulation are conveniently stored as Excel files.

The Italian government has put in place a process for evaluating energy sold to the distribution network as well as an incentive scheme for energy shared by the CSG. The minimum between the energy injected and withdrawn from the distribution network within the same hourly period is known as the shared energy. It is mathematically expressed as:

$$SE_h = min(\Sigma w_{i,h}; \Sigma i_{i,h}) \tag{1}$$

$w_{i,h}$ and $i_{i,h}$ represent the energy withdrawn from and fed into the distribution network by the i-th user during the h-th hour. In the case of CSGs, the energy injected into the distribution network is the quantity produced after accounting for self-consumption by common loads. For each MWh of shared energy, the CSG is awarded with an incentive tariff worth 109 euros.

As previously mentioned, the energy injected into the grid is paid at market price as well. Namely, the price is the hourly zonal price (PZ). The software allows you to supply a file containing the hourly PZ or a specific year, or you may specify a constant value. The income generated by the selling of energy to the distribution network can be easily calculated like:

$$RID_h = PZ_h * \sum i_{i,h} \tag{2}$$

In the above formula, PZh represents the zonal price at time h.

The three stages of the devised methodology are depicted in Fig. 2.

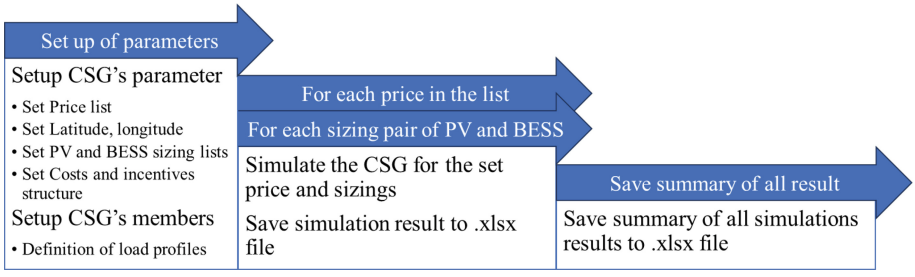

Fig. 2. Simulation workflow.

These are initialization of parameters, simulation, and results saving for further analysis. The PZ, and the geographic coordinates (latitude and longitude) of the CSG,

must be specified during the initialization process to estimate the photovoltaic (PV) system output for which the PVGis API has been used. After that, a list of PV and BESS sizes for which simulations are to be run can be defined. The unit costs for the PV system (€/kWp), the electrochemical storage system (€/kWh), the infrastructure implementation (€/kW), and the labor (€/kW) must also be specified to perform the economic simulations. The costs of capital investments (CAPEX) are then estimated using the previously mentioned elements. The costs of management and insurance are then asked to be provided to correctly estimate operating expenses (OPEX). The type facilities can be chosen from pre-installed categories in the following phase. Since the load curve of common loads oversees the PV system's instantaneous self-consumption of energy, it is also crucial to characterize it. Next, a list is constructed that contains the cartesian product of the PV system powers and the designated storage system capacities. Numerous techno-economic data are calculated for every single option (that is, PZ, PV size, and BESS capacity combinations). The main techno-economic parameters that are computed are the energy injected into the distribution network at each period, the energy withdrawn from the distribution network at each period, the self-consumed energy during each period, the hourly shared energy, the total energy bill for the CSG and the revenues generated by the selling and sharing of energy.

The approach enables the possibility to analyze investment scenarios that involve a partnership with a third-party actor who contributes initial funding (such as an energy service company, or ESCo) in exchange for a share of the profits made. If a non-member stakeholder finances the development of the plant and facility, its earnings come from selling electricity to the distribution network and from a portion of the incentive gained from members sharing electricity. As a result, the allocation of incentives [27] is the subject of a private contract made between the CSG and the external investor. Various methods are put forth in the literature for a proportionate and meritocratic allocation, based on game theory [28] or key performance indicators [29]. The idea that the CSG always bears the operational costs (OPEX) is another crucial one. Various financial factors are calculated for each simulated scenario to conduct a single evaluation. The net present value (NPV), internal rate of return (IRR), profitability index (PI), and the payback time (PBT), which is the point at which the cash flow turns positive, have all been calculated using the discounted cash flow approach. An investor can customize the investment based on its financial viability and the anticipated return for the CSG's members by analyzing these scenarios.

The total revenue received in the first year of operation, the variation in CSG expenditure (calculated by comparing the situation in which the CSG is not created), and the shared to produced energy ratio are additional information that have been computed to evaluate the investment.

With the proposed methodology a vast number of scenarios can be simulated in a brief time. For this reason, it is often useful to skim the results of the simulation according to specific requirements. In the specific case, authors decided to filter results that do not ensure a shared energy to produced energy ratio greater than 65%. As a matter fo fact,this choice reduce the number of options that do not adequately utilize energy produced locally, thus providing only solutions that satisfy a certain level of adequacy. Only the instances where the cost reduction for CSG is higher than 5% were retained to

further narrowing down the selection of findings. This way, a restriction is put in place with the intention of giving the participants in the collective self-consumption system an economic benefit baseline. Lastly, a second filter is applied to remove all simulations linked to a negative NPV value. Next, the new dataset is sorted by PI values that are getting lower. This makes it possible to quickly scan through profitable scenarios.

In the following section an analysis of the results generated for a case study is proposed.

3 Case Study

By examining the correlations between the variables and important system parameters like PV, BESS, and PZ, the analysis seeks to examine the landscape of created scenarios and the numerous aspects that define them. By examining the many KPIs of the system under consideration, the goal is to offer stakeholders in the energy industry relevant and useful information. To accomplish this goal, a CSG has been simulated using the approach presented in the preceding chapter. The simulations were conducted for various PV, BESS, and PZ values as well as under various investment realization scenarios. The case study foresees the economic assessment of an ESCo realizing the investment and providing advantages to the residents. It should be noted that operational expenses are in any case borne by the CSG. The sale of produced electricity to the distribution grid and a set portion of the incentives obtained from energy sharing among CSG members are the two main sources of income for the ESCo. This share has been set at 50% for the sake of this study, although it might be changed based on agreements reached between the parties.

Eight BESS capacities have been instantiated (0, 5, 7.5, 10, 12.5, 15, 17.5, and 20 kWh), while seven PV sizes have been assumed for the production and storage plants (5, 7.5, 10, 12.5, 15, 17.5, and 20 kWp). A total of 56 combinations are obtained by taking the cartesian product of the capacities. Various levels of energy prices in the wholesale market have been taken into consideration when evaluating the influence of energy prices: 50 €/MWh, 100 €/MWh, 150 €/MWh.

The other key simulation parameters used in the CSG simulation are displayed in Table 1. Thus, a CSG with twenty members has been established. Members were created using loads that reflect typical users. These typical users, which stand in for the CSG members, are a working couple between the ages of 30 and 64 (WC 30–64), a retired couple (RC), and a working couple with two kids where one of the parents works from home (CWK). Table 2 reports general information on both the annual usage and the total number of users instantiated in the setup.

The daily load profile for each typical user is displayed in Fig. 3. The disparity in users' attitudes toward energy utilization during the day is noticeable. Figure 4 shows an example of the same kind of graph as Fig. 3 for the load of common utilities.

Table 1. Simulation parameters

Parameter	Value
Latitude	39.205
Longitude	9.130
PV unitary cost (€/kWp)	1,100
BESS unitary cost (€/kWh)	1,000
Infrastructure unitary cost (€/kWx)	100
Labor unitary cost (€/kWx)	300
Management cost (€/kWx)	10
Insurance	0.5% of CAPEX
Discount rate	6%
Annual percentage rate	6%
Latitude	39.205

Table 2. Users' information

Name	Yearly consumption (kWh)	Number instantiated
WC 30–64	3,309	8
RC	2,351	6
CWK	5,841	6

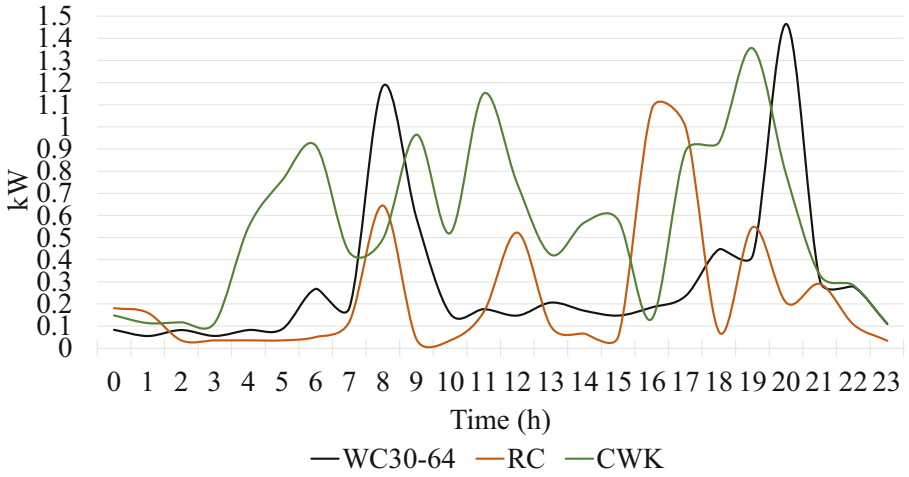

Fig. 3. Load profile of users' categories for a typical day.

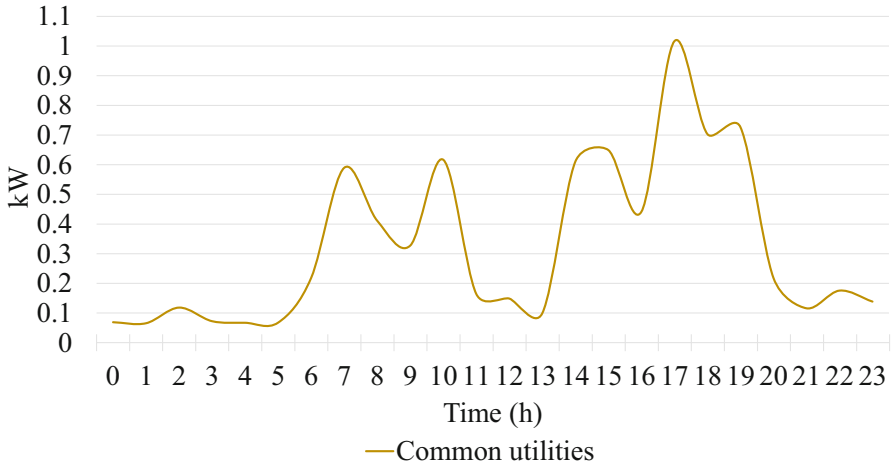

Fig. 4. Load profile of the common utilities for a typical day.

4 Results and Conclusions

After simulating and applying the procedure of results selection described in the methodology section, the total number of scenarios that foresees an ESCo assisting the investment for the CSG's facilities is reduced to 46. A statistical summary of results is reported in Table 3, while the first 5 results obtained with the sorting procedure (by descending value of PI) are reported in Table 4.

Table 3. Summary statistics: ESCo investing.

Statistic	CSGExpenditureVariation	NPV	TIR	PI	PBT	CAPEX	OPEX	SharedProducedRatio
mean	−9%	7,149.03	9%	126%	13.41	30,342.39	371.82	90%
std	2%	5,577.95	3%	22%	3.28	10,395.43	134.09	3%
min	−15%	12.38	6%	100%	7.80	7,500.00	87.50	82%
25%	−10%	2,643.03	7%	110%	11.21	23,500.00	292.50	88%
50%	−9%	5,910.30	9%	123%	13.13	30,375.00	376.25	91%
75%	−8%	10,780.98	10%	136%	15.73	38,000.00	465.00	92%
max	−5%	22,809.48	15%	176%	18.98	52,000.00	660.00	94%

Most interestingly, the average expenditure variation for the CSG stands at 9%. PBT for investment, with the current apportionment of the incentive, is slightly high and might not be appealing for an investor. Despite the not so inviting statistics, the first five results reported in Table 4 show some promising investment scenario for the ESCo and relevant returns for the CSG too. Interestingly, these are associated with a high price of energy which results in higher revenues generated by the sale of energy and with the absence of a storage system which, inevitably, increases the CAPEX and,

Table 4. First five results of the simulation ordered by descending PI, ESCo investing.

FirstYearRevenue	CSGExpenditureVariation	NPV	IRR	PI	PBT	CAPEX	OPEX	PV	BESS	PZ
6,615	−10%	22,809	15%	176%	7.80	30,000	350	20	0	0.15
5,058	−8%	17,097	15%	176%	7.80	22,500	262	15	0	0.15
3,406	−7%	10,917	15%	173%	7.99	15,000	175	10	0	0.15
5,692	−9%	18,687	14%	171%	8.09	26,250	306	17.5	0	0.15
4,079	−7%	12,695	14%	168%	8.32	18,750	218	12.5	0	0.15

consequently, the investment profitability. Results also show that the maximum capacity of PV is required by the investment scenario that provides the highest value of PI.

Another insightful analysis is to devise which variable most influences PI's value. To this end a feature analysis has been performed. The analysis's findings are presented in Fig. 5 for single terms, as well as for interacting terms.

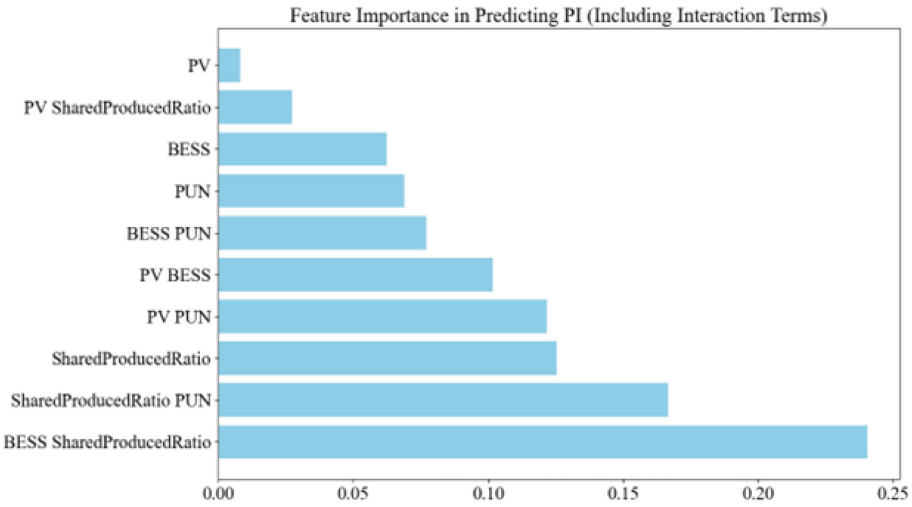

Fig. 5. Feature importance on PI

Interestingly, the most influential term on PI is given by the interaction of BESS and *SharedProducedRatio*: the installation of a storage system limits the sharing capability within the CSG, thus reducing the income generated by the incentive and increasing CAPEX due to the BESS presence, finally having a relevant negative impact on PI.

This research provides an in-depth analysis of energy communities, concentrating on Collective Self-Consumption Groups in Italy. The goal of the authors' multi-criteria techno-economic framework is to democratize local energy generation and consumption by assessing several condominium facilities sizing scenarios. The authors evaluated the social and financial benefits of various setups for a case study using simulation tools based on Python while taking financial indicators into account. In addition to adding to the body

of knowledge on renewable energy communities, the study offers stakeholders—such as investors and policymakers—useful information that will help them make decisions as we move toward more decentralized and sustainable energy systems.

The findings of the simulation of a case study are described and summarized, and an analysis of the most relevant parameters is provided. Resulting scenarios show there are wide margins for investing that can satisfy various requirements concerning capital expenditure, saved costs, and return on investment.

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