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Multi-objective battery sizing optimisation for renewable energy communities with distribution-level constraints: A prosumer-driven perspective

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ABSTRACT

A Renewable Energy Community (REC) is a legal entity aggregating different users sharing their own resources to reduce both electricity bills and CO_2 emissions. This paper presents and analyses the impact of a bi-objective strategy to optimise the capacity of the Battery Energy Storage Systems (BESSs) of REC prosumers equipped with photovoltaic (PV) generators. The optimisation problem is solved through a custom implementation of the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and has two contrasting objectives: maximising the self-sufficiency of the REC from the main grid, while minimising the BESS capacity of all REC members. A key novelty of this study is the prosumer-driven perspective, which allows to exclude the REC members who do not want to install a BESS through a linear optimisation constraint. Moreover, the proposed approach ensures that probabilities of over- or under-voltages are compliant with the limits specified by Distribution System Operators (DSOs). Such probabilities, as well as the line and BESS losses, are estimated within the optimisation loop through grid-level simulations performed in OpenDSS. Both a standard peer-to-grid (P2G) and a more REC-oriented peer-to-peer (P2P) energy sharing policy are analysed and their performance is assessed in different seasons and considering both the current energy demand and a possible future scenario, in which electrical heat pumps are widely used. The results of a case study based on a modified version of the IEEE 906-bus European Low Voltage distribution grid show that a if the total BESS capacity assigned to all REC prosumers exceeds a given threshold value, the benefits for the REC become minor. Assuming to choose the optimal BESS capacity solutions corresponding to the threshold value in the summer season (i.e., when PV and BESSs are most exploited), the overall energy losses are reduced roughly by 20%–40% for both P2G and P2P battery controls. The CO_2 emissions instead, are reduced by 10% to 50% with the P2P policy having a slight edge over the P2G one. The P2P energy sharing policy spreads the economic benefits of energy savings more evenly among REC members, and the return on investment is generally higher if the electricity demand increases.

1. Introduction

Rooftop photovoltaics (PV) is by far the most exploited clean energy source at the residential level, and the number of PV installations in the EU is expected to increase by 40 GW by 2024 [1]. Since the solar radiation is a variable source, it is well known that the Battery Energy Storage Systems (BESSs) can improve the exploitation of the total energy by storing the excess power available at a given time in order to shave and shift the peak power demand [2]. This solution proved to be economically viable [3], particularly in scenarios where multiple users pool their batteries to create virtual storage systems.

In this context, an important role could be played by the *energy communities*, i.e. legal entities aggregating prosumers willing to share their own energy resources to decarbonise the building stock and better exploit the locally generated power. The concept of *Renewable Energy Community* (REC) was formally defined by the EU commission in the European Renewable Energy Directive 2018/2001 [4]. In particular, the Commission states that part of the energy consumed in a REC should be provided by renewable sources and the consumption should happen in close proximity to the production site. Moreover, the prosumers should be allowed to participate on a voluntary basis, without involving energy market operators (to ensure a fair cost of energy for

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all REC members). Of course, an effective management of RECs poses a variety of business [5], security and technical challenges [6]. Among them, finding the optimal BESS capacity of every member is a critical issue, that has been tackled in a variety of ways over the last few years, but usually from the standpoint of Distribution System Operators (DSOs). Conversely, in this paper the optimal BESS sizing problem is addressed from the perspective of REC members. In particular, the main contributions of this work are summarised below

- A bi-objective optimisation strategy, rather than a classic single-objective one, maximises the energy self-sufficiency of a REC while minimising the total amount of installed BESS capacity.
- Unlike the usual DSO-driven perspective, the BESS siting is limited by the prosumers' willingness to install a battery. Thus, the BESS locations become a constraint rather than a goal of the optimisation problem.
- A custom implementation of the Non-dominated Sorting Genetic Algorithm-II is developed [7], allowing for multi-core processing and careful code optimisation.
- Thanks to this implementation, grid-level simulations are performed with a higher time resolution than the majority of the related work. These simulations provide an accurate estimate of the risk of over- and under-voltages, of the losses over the distribution lines and due to battery charging/discharging.
- The optimisation loop excludes the solutions causing an excessive over- or under-voltage risk on the grid, in compliance with the DSO requirements.
- A variety of conditions is analysed, i.e. changing the energy sharing policy, the season of the year, the load demand and the share of prosumers installing a BESS.

The rest of this paper is structured as follows. In Section 2, the purpose of this work in the context of the related work is explained more in detail. In Section 3, first the optimisation problem is formalised. Then, key details of the custom NGSA-II implementation are presented. Section 4 summarises the main settings of the different simulated scenarios, while the optimisation results in a meaningful case study are shown and commented in Section 5. A further analysis of the impact of BESS capacity optimisation in terms of losses, CO_2 emissions and economic profitability is reported in Section 6, while Section 7 concludes the paper.

2. Related work

As briefly outlined in the Introduction, the problem of BESS sizing optimisation (both with and without siting) has been widely explored over the last few years. However, the approach proposed in this paper is inherently different from others, as we assume that the BESSs are neither managed nor owned by a DSO, but rather by REC members themselves.

For this reason, a first major distinctive feature of this study is that the storage capacity values are the only decision variables of the problem, whereas BESS locations are not. Indeed, even though potentially all REC members could be interested in installing a BESS, in practice not all of them could be able or willing to do so. Thus, some prosumers' sites should be explicitly excluded from the optimisation problem. To the best of Authors' knowledge, the study in [8] is the only one in which optimal BESS sizing relies on a prosumer-driven, peer-to-peer energy sharing policy (in which REC members can trade electricity between each other). Though simulating an entire year with a small time step, the case study in [8] includes solely six buildings equipped with BESSs and does not account for possible voltage level violations. This happens because minimising the risk of over-voltages and under-voltages is mainly a DSO's responsibility and not a REC objective. Hence, voltage fluctuations reduction is usually included in BESS optimisation problems with a DSO-driven perspective, such as [9,10], sometimes along with the minimisation of the installed BESS capacity [11]. It is however of crucial importance for a REC to avoid power curtailments by the DSO due to voltage violations. Therefore in the approach described in this paper, the probability of over- and under-voltages is used as a constraint for optimal BESS sizing rather than an objective function.

A second key difference between the methodology described in this paper and other works on the same topic is the selection of the objective functions. So far, due to the DSO-driven perspective, the objective functions are usually either profit maximisation or system cost minimisation. An example of the former type is the solution proposed by Khaboot et al. [12], where a genetic algorithm is used for BESS sizing under the assumption that all buses are available for BESS placement. The BESS optimisation techniques described in [13] and [14] aim at maximising the economic revenues for DSOs by using a genetic algorithm and particle swarm optimisation respectively. Examples of system costs minimisation are instead reported in [9,15,16]. In [15], for example, the Authors solve the BESS placement and sizing problem by using a Monte Carlo embedded differential evolution algorithm on a daily basis with a hourly time step. Daghi et al. [16] developed a methodology involving fuzzy logic to model uncertain input profiles and probabilistic optimal power flow for short-term BESS scheduling optimisation. Mazza et al. [9] propose a custom genetic algorithm paired with a decision-making model considering both voltage and reverse power flow constraints.

It is worth recalling that a number of multi-step or multi-objective optimisation problems have been recently formalised to improve the performance of distribution systems with BESSs. For example, Sardi et al. [17] analyse the issues of BESS sizing, placement and operation in RECs for losses minimisation, power factor and voltage profile stabilisation and demand curve flattening. Giannitrapani et al. [18] perform a two-step optimisation, i.e. first they apply a heuristic approach for BESS siting and then an optimal power flow for BESS sizing. Xiao et al. [19] apply a two-step heuristic optimisation procedure where a genetic algorithm takes care of BESS sizing/siting while power losses are minimised through optimal power flow scheduling. Saboori et al. [20] rely on particle swarm optimisation to minimise both the average energy which is not supplied and the BESS costs.

In this paper, the joint minimisation of the share of electrical energy absorbed from the main grid and the total capacity of the BESSs assigned to the interested REC members is regarded as a desirable goal for prosumers and makes the optimisation problem inherently a bi-objective one. The choice of these objective functions stems from what the EU Commission thinks a REC should be [4], i.e. a legal entity that is supposed to make the energy districts independent from the main grid and reduce the electricity prices through an optimal exploitation of DERs.

A final important distinctive feature of this paper is the higher time resolution (i.e., 15 min) and the longer time horizon (i.e., up to 1 year) of the grid-level simulations performed while solving the optimisation problem. Indeed, in the majority of other studies [10,13,15,19,21], the time step is just one hour and the simulations are seldom performed in different seasons.

3. Methodology

As briefly explained in the Introduction, in this paper we aim at addressing both the problem of BESSs capacity minimisation for each REC member and the minimisation of the amount of electrical energy absorbed from the main grid. In the following section, firstly the optimisation problem is formalised; then the key steps for its solution and some implementation details are reported.

3.1. Problem formulation

Even though it is well known that the use of BESSs can improve both voltage stability and PV energy self-consumption, a careful evaluation of the trade-offs needed to make BESS deployment energetically, environmentally and economically profitable is not an obvious problem, especially in the case of RECs due to the differences in both prosumers' behaviour and energy sharing policy. In this paper, a bi-objective optimisation strategy is used for BESS sizing, in order to analyse the best trade-off between REC self-sufficiency improvement and BESS capacity increase, while making a widespread use of BESSs acceptable for DSOs. The former quantity is also an indicator of possible environmental and economic benefits, whereas the latter is the factor that mainly affects BESS deployment costs. The Pareto front of non-dominated solutions computed in different scenarios and in heterogeneous operating conditions will allow us to decide to what extent BESS deployment is feasible and profitable. For the sake of simplicity and without loss of generality, let us assume that all the grid users connected to the same substation are regarded as members of the same REC. All of them are already equipped with a PV generator, but not all prosumers might be interested in installing a BESS. Within the REC, bidirectional power flows may occur over the lines of the distribution system, and the reverse power flows may occasionally reach the secondary winding of the transformer located in the substation connecting the REC with the main grid. In these conditions (which occur whenever the PV power exceeds the total load demand and cannot be stored in the BESSs), the surplus of generated power can be injected into the grid. When the electricity power consumption is instead higher than the generation, the exceeding demand of electricity has to be absorbed either from the batteries or from the main grid. Let us assume that the REC consists of N members and let $[t_0, t_0+T]$ be the period of interest of duration T chosen for optimal BESS sizing. If $\mathbf{x} = [x_1, \ldots, x_N]^T$ is the vector of the BESS capacity values assigned to the REC members, the bi-objective optimisation problem addressed in this paper can be compactly formalised as follows, i.e.

$$\min_{\mathbf{x}} \ (C_T(\mathbf{x}), G_A(t_0, T, \mathbf{x})) \tag{1}$$

subject to:

$$C_{\min} \leq x_n \leq C_{\max} \qquad n = 1, \ldots, N \tag{1a}$$

$$\Pr\left\{V_L \leq V_b^p(t_0, T, \mathbf{x}) \leq V_U\right\} \geq q_\alpha \qquad b = 1, \ldots, B \quad p = 1, 2, 3 \tag{1b}$$

$$U\mathbf{x} = \mathbf{0} \tag{1c}$$

where the definitions of the objective functions and the meaning of the constraints is reported in detail below. In particular,

$$C_T(\mathbf{x}) = \sum_{n=1}^{N} x_n \tag{2}$$

represents the total capacity of all BESSs deployed in the REC, and

$$G_A(t_0, T, \mathbf{x}) = \frac{E_G(t_0, T, \mathbf{x})}{E_L(t_0, T, \mathbf{x}) + \sum_{n=1}^{N} E_{D_n}(t_0, T)} \cdot 100 \tag{3}$$

is the so-called *grid absorption coefficient*, namely the share of energy (expressed as a percentage of the total REC energy requirement) that has to be actually absorbed from the main grid in the time interval $[t_0, t_0+T]$. More in detail, in (3) $E_G(t_0, T, \mathbf{x})$ is the total energy absorbed by the REC through the transformer of the substation when the PV power either directly generated or stored into the BESSs is not enough to ensure the complete REC self-sufficiency. Functions $E_L(t_0, T, \mathbf{x})$ and $E_{D_n}(t_0, T)$ at the denominator of (3) represent the total energy losses (due to the non-negligible line impedances and the limited charging/discharging BESS efficiency), and the total energy demand of the n-th REC member. Note that terms $E_{D_n}(t_0, T)$, obtained by integrating the load power profiles over time, do not depend on the BESS capacity values $\mathbf{x}$. In the trivial case of purely passive users, $G_A(t_0, T, \mathbf{x})$ is 100%, while its value decreases (i.e., self-sufficiency improves) as the penetration of both PV generators and BESSs grows.

In the optimisation problem (1), three constraints are included.

- Constraint (1a) limits the BESS capacity range between given minimum and maximum values (denoted with $C_{\min}$ and $C_{\max}$, respectively) due to technology or regulatory requirements.
- Constraint (1b) ensures that in the time interval $[t_0, t_0 + T]$ the Root Mean Square (RMS) voltages $V_b^p(t_0, T, \mathbf{x})$ of the B three-phase buses connected to the REC members are included within the DSO-compliant interval $[V_L, V_U]$ with a probability at least equal to q_α. The values of V_L, V_U and q_α depend on local, national or international regulations about voltage stability. In general, $B \geq N$ due to the presence of zero-injection buses, which are very common at the distribution level.
- Finally, the linear equality constraint (1c) prevents that BESSs are assigned to the REC members that do not want or cannot install them. In particular, if U is a $N \times N$ diagonal matrix, if the i-th diagonal element is different from 0 (i.e., equal to 1), the i-th equation extracted from (1c) is satisfied if and only if $x_i = 0$. This means that the nonzero diagonal elements of U are used to identify the REC members that have to be excluded from optimal BESS sizing.

The values of the various parameters listed above depend on the REC model considered and are reported in Section 4 for the specific case study considered in this paper. It is important to highlight that the objective function (3) and the constraint (1b) not only are strongly nonlinear, but they can also be hardly formulated in an explicit analytical form. Hence, the computation of the grid absorption coefficient and the probability of voltage violations can only be obtained through numerical simulations. Moreover, the results are influenced by the actual PV generation, the load power profiles and the energy sharing policy adopted by the REC members.

3.2. Problem solution

The BESS optimisation problem (1) was solved by means of a custom implementation of the NSGA-II algorithm. The BESS capacity values of the N REC members (namely the decision variables of problem (1)) are regarded as the genes of an N−sized chromosome. The NSGA-II algorithm requires an initial $2M$−sized population of chromosomes, M of which change at every iteration as a result of the evolutionary process. Of course, the value of M as well as the genetic variety of the initial population must be large enough to ensure a thorough exploration of the solution space. A simplified flowchart of the developed implementation is shown in Fig. 1.

The genetic algorithm is applied to a multi-parametric REC model, whose behaviour depends on a variety of inputs, such as

(a) the *load consumption profiles*, which depend on the profile temporal resolution, the type of load (e.g., residential or commercial), the buildings occupancy [22], the users' behaviour and habits, the grid geographical location and the season of the year;
(b) the *grid model*, which includes the network topology, the line parameter values, the transformer features and the nominal load values;
(c) the *PV generation profiles*, which depend on the maximum power of the PV generators deployed at REC members' sites as well as on the daily solar irradiance and temperature patterns in different seasons of the year.
(d) the *BESSs capacity values* could potentially take any real value within $[C_{min}, C_{max}]$, but in practice are quantised. This is due to the fact that the capacity of a single cell cannot be arbitrarily small, but depends on the battery technology. Therefore, even if the optimal BESS sizing problem formally is continuous, in practice it becomes discrete (i.e., combinatorial), thus justifying the use of a genetic algorithm to solve (1). Note that if there are sites where BESSs cannot be installed due to constraint (1c), the corresponding genes are steadily set to 0 in all chromosomes and for all generations.

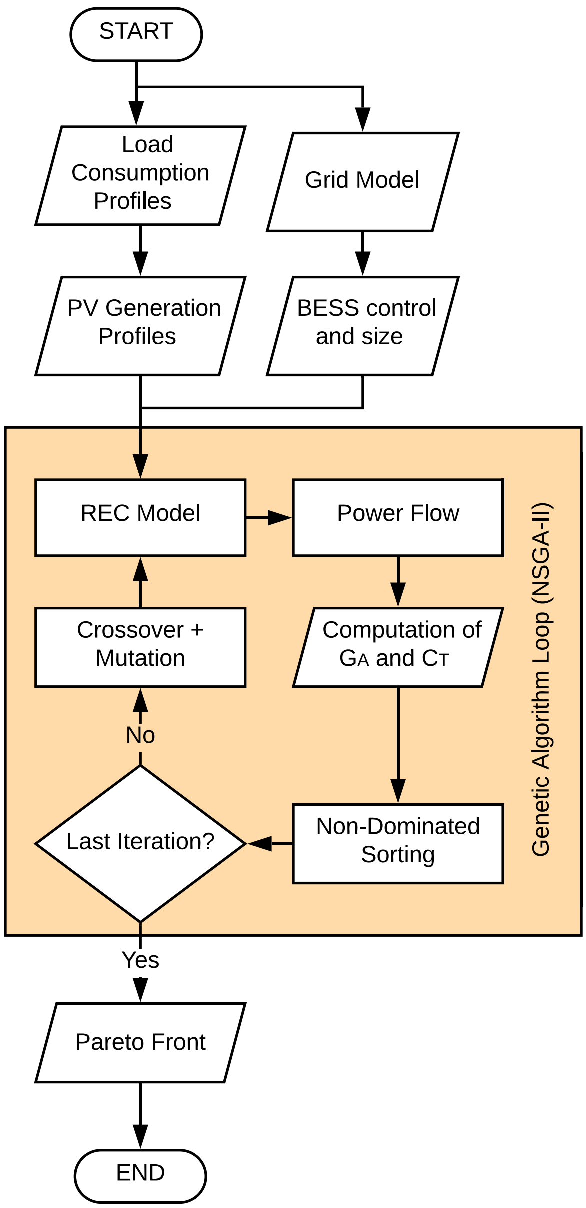

Fig. 1. Simplified flowchart of the algorithm implemented to solve the BESS sizing optimisation problem from equation (1).

A quasi steady-state power flow analysis is repeatedly performed in OpenDSS for each chromosomes of the population in the time interval $[t_0, t_0 + T]$, with a predefined time step. This iterative power flow analysis returns accurate time series of the power flows within the REC, the corresponding losses (used to compute (3)) and the bus voltage values. The probability of exceeding the ends of interval $[V_L, V_U]$ has to be checked to meet constraint (1b).

It is important to emphasise again that such grid-level simulation results depend also on the energy sharing policy chosen by the REC members. In the present study, two alternative energy sharing policies are implemented to schedule the BESS power flows between REC members, i.e. the classic peer-to-grid (P2G) approach and a custom peer-to-peer (P2P) policy (firstly introduced in [23] and then improved in [24]). In the P2G approach each REC member manages its own BESS, regardless of the state of the others and the neighbours' needs. In this case, power flows between the REC peers are possible but not implemented through a specific BESS control. Conversely, the P2P policy specifically promotes the exchange of energy between prosumers depending on their actual supply and demand as well as the state of charge (SOC) of all the BESSs at a given time. Further details on P2G and P2P BESS control rules are summarised in Appendix A. The losses due to BESS charging and discharging are also taken into account in the simulations since they may significantly affect the outcome of this study, as it will be shown in Section 6.

Once the results of the OpenDSS quasi steady-state power flow simulations are completed for all the chromosomes of the available population, the objective functions (2)–(3) are computed and the constraint conditions (1a)–(1c) are checked.

The feasible solutions are kept and ranked on the basis of the so-called *non-dominated sorting criterion* [7]. With reference to cost functions (2) and (3), a solution $\mathbf{x}_i$ dominates a solution $\mathbf{x}_j$ if

$$\begin{cases} G_A(T, \mathbf{x}_i) < G_A(T, \mathbf{x}_j) \\ C_T(\mathbf{x}_i) \le C_T(\mathbf{x}_j) \end{cases} \vee \begin{cases} G_A(T, \mathbf{x}_i) \le G_A(T, \mathbf{x}_j) \\ C_T(\mathbf{x}_i) < C_T(\mathbf{x}_j) \end{cases} \tag{4}$$

By repeatedly applying condition (4), the $2M$ chromosomes of a given generation are partitioned into subsets (called "fronts") in such a way that the objective function values associated with all the members of the f-th front are *dominated* by the solutions of the $(f-1)$-th front only. The first front, which contains the solutions that are not dominated by any other, is the "Pareto front" of the considered population. In addition, the so-called *crowding distance* associated to each solution of a given front is computed, as explained in [7]. Given that just M of the existing solutions have to be selected to create a new generation, if the chromosomes of the non-dominated front are more than M, only those with the largest crowding distance are retained. Conversely, if the Pareto front elements are less than M, the missing ones are taken from the following ordered dominated fronts, always starting from the chromosomes with the largest crowding distance values. The algorithm returns a population of M chromosomes, whose genes are combined through binary tournament, crossover and mutation, as customary in genetic algorithms, to obtain M new solutions that are added to the parent ones. The results of this last step are fed back into the REC model and the algorithm runs until the chromosomes of the Pareto front no longer change significantly. Of course, the number of generations needed to reach convergence depends on the features of the considered case study.

3.3. Implementation details

The algorithm shown in Fig. 1 is mainly implemented in Matlab, but it is also interfaced with the software OpenDSS which is used to run grid-level simulations within the optimisation loop.

One of the most important features of the NSGA-II algorithm is that the computation of the objective functions values associated with each BESS sizing configuration can run in parallel within multiple threads, thus greatly reducing processing times. To this end, the functions of the Matlab Parallel Computing Toolbox are used. Moreover, since the hot spot of the whole software application is the power flow analysis for each solution, the OpenDSS parallel machine features are exploited to reduce the processing time of grid-level simulations. As a result, the whole application can be split into multiple threads running in up to 30 processing cores, supported by 2 banks of 3600 MHz DDR4-RAM of 32 GB each. Each thread computes the objective function and returns a solution of the optimisation problem. The obtained results are saved into Matlab structures that are finally merged before running the non-dominated sorting step of the NSGA-II. Since the 3.6 GHz processor runs at 2.2 GHz due to multi-threading, the overall speedup does not follow a 1:1 relationship with the number of cores. Nevertheless, it is still sizeable, i.e. around 12 times greater than standard non-parallelised solution, in accordance with the conclusions reported in [25].

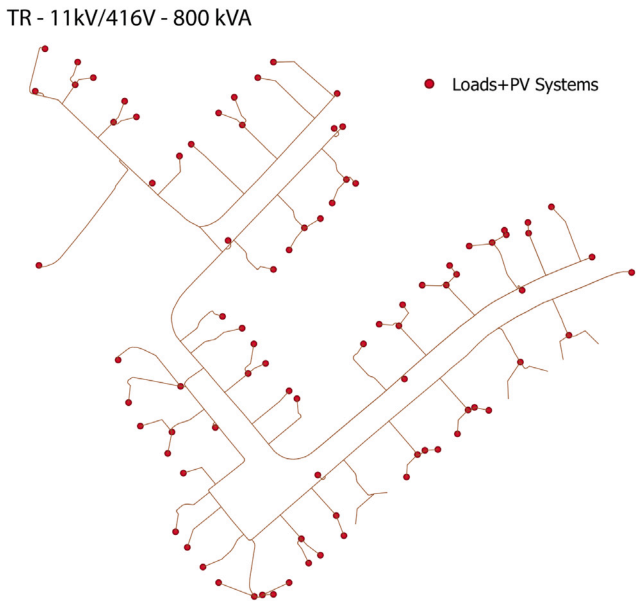

Fig. 2. Structure of the IEEE 906-bus LV Test distribution system.

4. Case study description

This Section provides an overview of the case study chosen to evaluate the performance and the impact of the proposed optimal BESS sizing approach. Firstly the details of the REC model are reported; then the optimisation and simulation settings in different scenarios of interest are described.

4.1. REC model and simulated scenarios

The European distribution grid consists, by a vast majority, of Low-Voltage (LV) sub-systems. Hence, the IEEE 906-bus three-phase LV test system was chosen to implement and simulate a REC. The reason underlying this choice is that i) all grid parameters are publicly available on the website of the IEEE Power and Energy Society (PES)[1], and (ii) the grid geographical extension is small enough to assume that all loads and PV generators belong to the members of a single REC. The structure of the grid is shown in Fig. 2.

The REC members' loads are connected to the buses highlighted with red dots in Fig. 2. In particular, the loads of the original IEEE PES model were replaced by the residential power consumption profiles synthesised by the software tool Load Profile Generator (LPG) [26]. Since LPG relies on complex multi-parametric bottom-up load models, a variety of parameters have to be set to generate the load consumption profiles of potential REC members. The most important parameters are: the type of dwelling (e.g., detached houses or buildings with multiple flats), the average seasonal electrical power consumption, number and age of occupants. In the current case study, the number of houses of different categories and their occupancy result from a preliminary urban and demographic analysis of the city of Bolzano, in the Italian Südtirol-Alto Adige autonomous province [27]. Two alternative scenarios are considered for the electrification of heating and cooling systems:

- *Present scenario*, in which the impact of heating and cooling on the total electrical energy consumption is assumed to be negligible (mainly because other fuels are used to serve this purpose);
- *Future scenario* in which, as a result of the aggressive EU directives for greenhouse gases emissions reduction [4], heating and cooling are entirely powered by highly efficient electrical heat pumps. In fact, the joint use of PV generation and electrical heat pumps is a well-known effective strategy to improve the energy efficiency class of buildings [28].

Table 1
Minimum and maximum values of the load consumption profiles synthesised with LPG and of the actual daily PV power generation peaks used to simulate present and future load scenarios (i.e., without and with widespread electrical heat pumps, respectively) in winter and summer and with either energy sharing policy (i.e., P2G or P2P).

Scenarios		Present (no heat pumps)		Future (with heat pumps)	
		min. [kW]	max. [kW]	min. [kW]	max. [kW]
Loads	Winter	39.1	363.6	72.9	422.8
	Summer	25.6	377.4	25.8	623.2
Peak PV	Winter	18.8	373.6	22.7	449.8
	Summer	245.4	410.2	295.5	493.9

The power consumption patterns in the future scenarios exhibit quite a different shape compared to the present scenarios, especially when the heat-pumps are fully operational (i.e., overnight in winter for heating, and in the central hours of summer days for cooling). As a result, the total yearly energy demand of future scenarios is about 40% greater than in the present ones, a figure which is just slightly higher than the value in [29], i.e., 35%.

In the present study, without loss of generality, all REC members are assumed to be equipped with a PV generation unit connected to the same buses highlighted with red dots in Fig. 2. The PV power profiles used for OpenDSS simulations rely on a built-in empirical model [30], which is based on two standard efficiency curves to describe the effects of PV modules temperature, solar irradiance and inverter efficiency on PV generation. The irradiance and temperature data were recorded in the ABD PV system installed at the Bolzano-Dolomiti airport (Bolzano, Italy) in 2017 (further details are reported in [31]). The PV modules have a minimum performance ratio of 77%, maximum of 100% and median of 91%. The rated power of each PV generation unit is sized in order to achieve about 30% of actual yearly self-sufficiency without any storage. This result is in line with the fact, from experimental evidence, the PV energy generated in many residential setups can hardly cover more than 30% of the yearly energy consumption, even when the total PV generation capability is considerably higher [32,33]. Moreover, increasing the PV penetration is not always possible, because a PV penetration higher than a certain threshold (around 45% in the considered case study) could cause excessive voltage violations, thus making constraint (1b) occasionally infeasible.

Table 1 summarises the main power generation/consumption profiles by listing the minimum and maximum values of both the aggregate load consumption profiles and PV power generation peaks under present and future load conditions (i.e. with or without heat pumps) in both winter and summer. In particular, the reported winter values refer to January (when the PV power generation is generally lowest), whereas the summer ones refer to August (when the mismatch between the PV power supply and the power demand is usually the highest). The impact of the electrical heat-pumps on power consumption is quite evident but partially covered by larger PV generators, as previously explained.

As far as the BESS sites are concerned, they depend on REC members' intention, as subsumed by constraint (1c). Since the number of deployed BESSs may strongly affect their optimal capacity, three alternative scenarios are analysed in which 25%, 50% or 75% of all REC members decide to install a BESS. Such scenarios in the following will be referred to as *conservative*, *neutral* and *aggressive*, respectively. In all scenarios, a different share of users uniformly spread over the grid (to avoid BESS clustering) is assumed to install a lithium-ion BESS. The

[1] https://site.ieee.org/pes-testfeeders/

Table 2
Problem-specific and NSGA–II parameter settings for optimal BESS sizing in the six scenarios $P25-P75$, $F25-F75$ described in Section 4.2.

	Parameters	Values
Problem-specific settings	Number of REC members N	90
	Number of buses B	906
	Initial time t_0	Jan. 1 or Aug. 1
	Time interval duration T	31 days (2976 15-min. time steps)
	Min. BESS capacity $C_{\min}$	1 kW h
	Max. BESS capacity $C_{\max}$	60 kW h
	Lower acceptable voltage V_L	0.9 p.u.
	Upper acceptable voltage V_U	1.1 p.u.
	Prob. of not exceeding voltage limits q_α	95% (per week)
	Matrix U of REC members' sites excluded from BESSs installation	Diagonal matrix with $N/4$ ($P25-F25$) or $N/2$ ($P50-F50$) elements $\neq 0$ All-zero matrix ($P100-F100$)
NSGA-II	Min. BESS capacity increment	1 kW h
	Number of chromosomes M	100
	Crossover probability	50%
	Mutation probability	Decreasing linearly from 25% to 10%
	Number of generations	50

round-trip BESS charging and discharging efficiency is set to 90% and the state of charge (SOC) for each battery is constrained between 10% and 90%, in compliance with the values reported in the literature for this particular technology [34,35].

From the combination of the aforementioned present or future load scenarios and the conservative, neutral and aggressive BESS penetration levels, six joint scenarios result. For the sake of brevity, in the rest of this paper they will be shortly denoted as $P25$, $P50$, $P75$, $F25$, $F50$ and $F75$, where letters P and F stand for "present" and "future", whereas 25, 50 and 75 refer to the percentage of REC members equipped with a BESS. In each combined scenario, the grid-level simulations are performed in four alternative operating conditions, i.e. for different seasons of the year (winter or summer, since it is reasonable to assume that the results in autumn and spring are intermediate) and considering either the P2G or the P2P energy sharing policy.

4.2. Simulation and optimisation settings

Two groups of parameters (whose values are reported in Table 2) have to be set to run the genetic algorithm. The first group is problem-specific and it is used to compute objective functions (2)–(3) and/or constraints (1a)–(1c) for each scenario of interest. The meaning of these parameters has been already defined in Section 3.1, but some of the values reported in Table 2 deserve some further explanation. In particular, the minimum BESS capacity C_{min} that can be assigned to every REC member is 1 kW h. This is the size of a very small battery [36], which can be used to extend the proposed study close to the case in which no BESSs are used. The maximum capacity C_{max} per REC member is instead 60 kWh. This is the maximum BESS capacity that can be regarded as acceptable in terms of size at a residential level, considering that its volume is about 1 m^3 based on the technical specifications of several manufacturers. The values of parameters V_L, V_U and q_α in (1b) ensure that the bus RMS voltage levels lie within ±10% of the nominal value with 95% probability, in compliance with the requirements of the EN Standard 50160:2009 [37]. A further parameter (not explicitly defined in Section 3.1, but essential to run the optimisation algorithm) is the time step of grid-level simulations. As highlighted in Section 2, this is set to 15 min because it provides a reasonable trade-off between computational burden and temporal resolution of the power flow analysis. In addition, 15 min is also the sampling period duration of the experimental irradiance and temperature patterns used for PV power profile generation and the reporting period length of second-generation smart metres currently deployed in Italy [38].

The second group of parameters in Table 2 refers specifically to NSGA-II settings. The first parameter in this group is the minimum BESS capacity increment. This is set equal to C_{min} and affects the quantisation of the possible solutions space, as well as the minimum variations of the values that can assigned to each gene. The value of M was tuned heuristically and it corresponds to the lowest possible number of chromosomes that ensure a trustworthy convergence of the Pareto fronts in all scenarios. Finally, the crossover and mutation probabilities are set as recommended in [7] to minimise the risk that the algorithm gets stuck in local minima.

5. Optimisation results

This section reports the results of BESS capacity optimisation in the previously described scenarios. The Pareto fronts of optimal solutions obtained after reaching NSGA-II convergence are shown in Fig. 3(a)–(f) for scenarios $P25-F25$, $P50-F50$ and $P75-F75$, respectively.

In all cases, the trend of the Pareto fronts is in line with the expectations, although it is just slightly visible in the conservative scenarios with 25% BESS penetration and P2G energy sharing policy. In fact, by increasing the total amount of BESS capacity C_T, objective function G_A decreases. This comes as no surprise as G_A is defined as the share of the electricity absorbed from the main distribution grid within the chosen time interval. Moreover, the G_A values in winter are obviously always greater than those in summer. The most relevant general remarks are summarised below.

- When the total BESS capacity is very small, the share of energy absorbed from the distribution grid depends mainly on seasonal factors. Indeed, when C_T tends to 0, all winter or summer Pareto fronts start approximately from the same G_A level. In the case at hand, the maximum G_A values range from about 50% in summer up to a value ranging between about 70% and 75% in winter depending on whether the load with or without heat pumps is considered. Furthermore, a minor difference exists between the starting G_A values of scenarios $P25$, $P50$, $P75$ and those of scenarios $F25$, $F50$, $F100$. Indeed, even if in the latter case loads are approximately 40% higher, their impact on G_A is mitigated by the fact that the PV generators are sized according to the nominal installed loads (as explained in Section 4.2).
- When C_T exceeds a given context-specific critical threshold, the reduction of G_A becomes negligible, i.e. smaller than 1%. Indeed, if there is neither enough available capacity before charging nor stored energy before discharging, increasing BESS capacity is not beneficial to REC members. When the total BESS capacity exceeds such a critical threshold, the stored PV energy is not enough to cover the residual demand. Hence, G_A tends to an asymptotic value. This value generally tends to increase as the BESS penetration grows because, for a given total capacity C_T, a higher number of distributed BESSs can be exploited more efficiently.
 Table 3 reports the approximate threshold C_T values in winter and in summer in scenarios $P25-F25$, $P50-F50$ and $P75-F75$

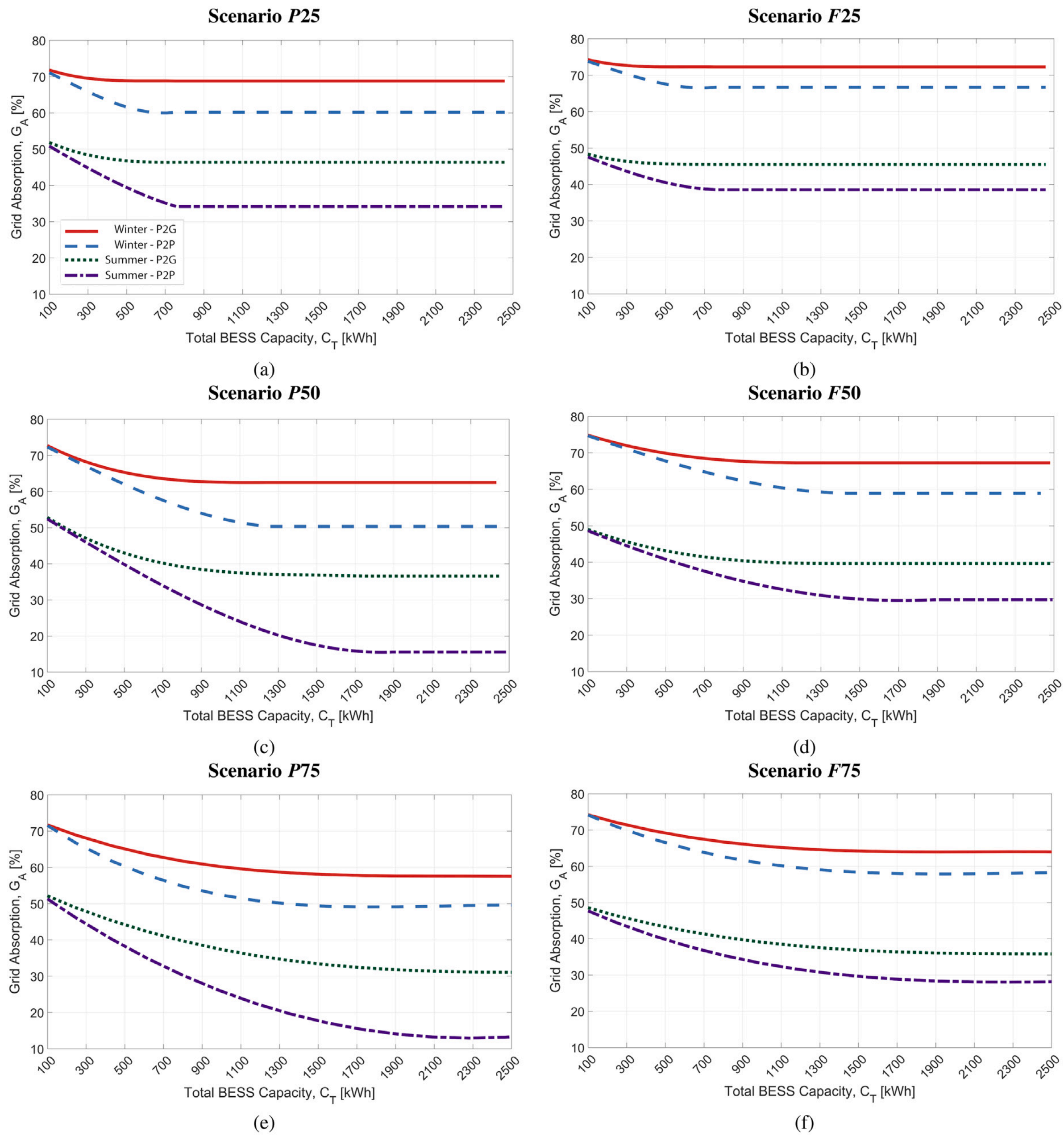

Fig. 3. Pareto fronts resulting from BESS sizing optimisation in scenarios $P25$ (a), $F25$ (b), $P50$ (c), $F50$ (d), $P75$ (e) and $F75$ (f). For each of them, four operating conditions are analysed, i.e. in winter or summer and by using a P2G or a P2P energy sharing policy within the REC.

when either the P2G or the P2P energy sharing policy is used. Quite interestingly, the threshold C_T values are quite independent of the load conditions. Thus, a single common threshold C_T value is shown for each pair of "present" and "future" scenarios. Of course, both the threshold values and the gap between the winter and summer ones increase as the BESS penetration grows, as expected. With the P2G sharing policy, the C_T thresholds exhibit a lower seasonal variability than using the P2P one. However, in the latter case the maximum threshold C_T values are higher because the P2P policy generally ensures a better exploitation of the available capacity, thus the G_A value decreases for longer C_T intervals.

- The main benefit of the P2P energy sharing policy is its ability to achieve the same performance as the P2G one with a lower total installed BESS capacity. When the P2P energy sharing policy is used, even if only 25% of REC members are equipped with a BESS, the other prosumers may indirectly benefit from their neighbours' BESSs in any case. When the P2G policy is adopted instead, the REC members that are not equipped with a BESS can only self-consume the power generated at a given time and sell the surplus to the DSO. Therefore, a gap exists between the Pareto fronts associated with the two policies which depends on both the BESS penetration level and the season. Interestingly, this

Table 3
Winter and summer threshold C_T BESS capacity values (expressed in kWh) in scenarios $P25-F25$, $P50-F50$ and $P75-F75$ when either the P2G or the P2P energy sharing policy are used.

		P25–F25	P50–F50	P75–F75
P2G	Winter	500	1100	1800
	Summer	500	1300	2100
P2P	Winter	800	1400	1800
	Summer	800	1800	2300

gap is not monotonic. Indeed, when the share of REC members installing a BESS grows from 25% to 50% the difference between the P2P and P2G fronts in the same season tends to grow, as expected. However, when the BESS penetration level exceeds 50% an opposite trend is observed. In fact, in the $P75-F75$ scenarios, the gap between the Pareto front is smaller than in the $P50-F50$ ones, and it would further decrease to negligible values if 100% of REC members installed a BESS (this case is not shown for the sake of brevity, as it is probably too extreme). This is probably due to the fact that as the number of REC members equipped with a large BESS grows, the prosumers' self-consumption capability improves. Therefore, they become more and mode independent of the energy surplus sold by their neighbours and the G_A values tend to become insensitive to which energy sharing policy is used.

- The loads increase due to the widespread use of electrical heat pumps in "future" scenarios does not change the main conclusions of the previous analysis. In fact, since the peak power of the installed PV generators grows to meet the greater demand, a higher BESS capacity is needed to reach the same G_A values as in "present" scenarios, thus it is not possible to reduce G_A down to the same levels. Generally, for a given C_T value, the G_A increase (ranging from a few percent points up to more than 10%) caused by the widespread use of electrical heat pumps is due to the higher share of the daily energy demand that is not covered by BESSs because their state-of-charge is too low.

Ultimately, we can conclude that if the installed BESS capacity is large enough and a P2P energy sharing policy is adopted, up to about 50% of the REC electricity demand (in winter) and more than 80% (in summer) can be covered by PV-based energy. For a given value of C_T, the P2P results are only slightly affected by the physical location of the deployed BESSs, although the losses may change considerably, as it will be shown in Section 6.

A final point that deserves attention is the probability of voltage violations, which is indeed taken into account in the solution of the BESS sizing optimisation problem through constraint (1b). According to the results of OpenDSS simulations, the probability that the RMS voltage levels exceeds the respective nominal values at every bus by more than ± 0.1 p.u. is around $10^{-5}-10^{-6}$ in scenarios $P25$, $P50$, $P75$ and slightly increases in scenarios $F25$, $F50$, $F75$. This increment is due to the larger power consumption fluctuations caused by the use of heat pumps. Moreover, in "future" scenarios, the probability of voltage violations tends to decrease as C_T grows, thus confirming that the BESSs positively contribute to grid voltage stabilisation, in accordance with other studies specifically focused on this topic [39]. More information about the impact of BESS deployment on the voltage levels can be found in Section 6.

6. Impact analysis of optimal BESS sizing

Even if all points of the obtained Pareto fronts provide potentially optimal solutions to problem (1), in the following the impact analysis of optimal BESS sizing is performed by choosing the solutions associated with the critical C_T thresholds reported in Table 3 in the summer season. In this way, the maximum self-sufficiency (and consequently the minimum G_A values) can be reached throughout the year.

Such solutions can be regarded as the reference ones to evaluate the efficiency, environmental and economic benefits of optimal BESS sizing in each of the considered scenarios compared to the case when no BESSs are used.

6.1. Bus voltage fluctuations

The effect of the chosen optimal BESS sizing solution on voltage stability can be observed in Fig. 4, which reports the box-and-whiskers plot of the normalised voltage values at all buses in scenarios $P25-F25$, $P50-F50$ and $P75-F75$ both without and with BESSs. In the latter case either a P2P or a P2G energy sharing policy is used. The box-and-whiskers plot confirms that BESS deployment reduce the range of voltage fluctuations compared to the case in which no batteries are included. Clearly, the probability that the bus voltage levels exceed the respective nominal values by more than $\pm 10\%$ is close to zero in the "present" load conditions and it is in the order of 1% in the case of a widespread use of electrical heat pumps. Thus, the implementation of constraint (1b) based on the requirements of Standard EN 50160:2010 [37] is certainly met and it is in line with the results summarised at the end of Section 5. It has to be noted that the range of bus voltage fluctuations depends on load conditions (in fact, it is larger in the "future" scenarios than in the "present" ones), but is quite independent of the BESS penetration. Moreover, if the loads with electrical heat pumps are considered, the P2P energy sharing policy is clearly preferable, since both the interquartile and the maximum voltage ranges are smaller than those obtained either with the P2G policy or when no BESSs are used. On the contrary, in the "present" load scenarios, the two energy sharing policies have a comparable impact on voltage fluctuations.

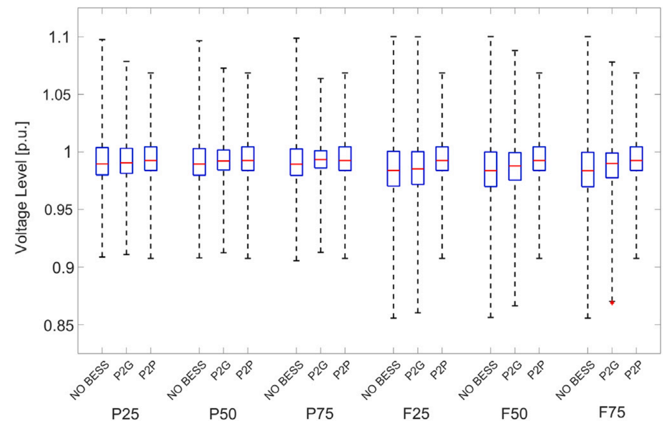

Fig. 4. Box-and-whiskers plot of the normalised voltage levels at all buses of the distribution grid under test over 1 year of simulations in scenarios $P25-F25$, $P50-F50$ and $P75-F75$ both without and with BESSs. In the latter case, either a P2P or P2G energy sharing policy is used. The BESS capacity values assigned to REC members in each scenario correspond to the C_T critical thresholds of the P2P and P2G summer Pareto fronts beyond which no significant reduction of G_A is observed.

6.2. Relative energy losses

The relative energy losses result from the ratio between the total energy (or average power) dissipated over the distribution lines or lost in BESS charging and discharging and the total gross energy (or average power) requirement of the REC in a given time interval $[t_0, t_0+T]$, i.e.

$$REL(t_0,T,\mathbf{x}) = \frac{E_L(t_0,T,\mathbf{x})}{E_L(t_0,T,\mathbf{x}) + \sum_{n=1}^{N} E_{D_n}(t_0,T)} \tag{5}$$

where $E_L(t_0,T,\mathbf{x})$ and $E_{D_n}(t_0,T)$ are the total energy losses and the electrical energy consumption of the n-th REC member, respectively, as they are defined in Section 3.1.

The bar diagram in Fig. 5 shows the relative losses estimated through one-year-long, grid-level OpenDSS simulations in the six scenarios under study. In particular, the relative losses estimated by assigning to REC members the BESS capacity values corresponding to the critical summer C_T thresholds reported in Table 3 are compared with the losses estimated when the PV generators are used without BESSs. Observe that the share of losses due to electricity distribution are shaded to distinguish them from the losses due to BESS charging and discharging. The results in Fig. 5 immediately show that in all scenarios the use of BESSs and the related energy sharing policies reduce the

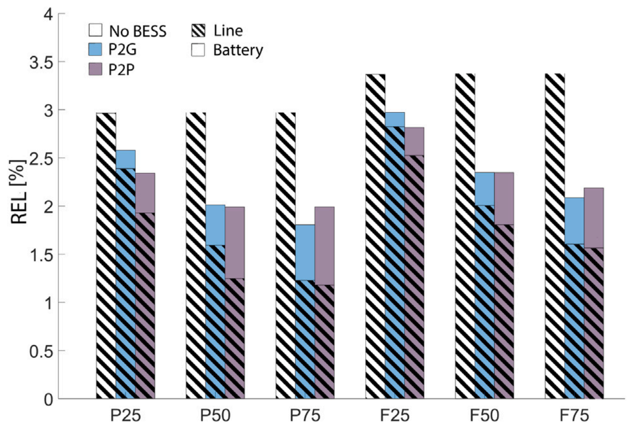

Fig. 5. Yearly relative energy losses (due to both electricity distribution and BESS charging/discharging) in scenarios $P25$, $P50$, $P75$, $F25$, $F50$ and $F75$ either with or without BESSs, handled by the P2G or the P2P energy sharing policy. The BESS capacity values assigned to REC members correspond to the C_T critical thresholds of the P2P and P2G summer Pareto fronts plotted in Fig. 3, beyond which no significant reduction of G_A is observed.

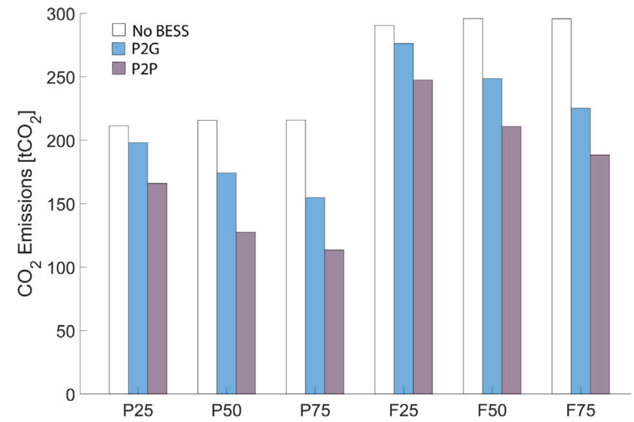

Fig. 6. Yearly total CO_2 emissions in scenarios $P25$, $P50$, $P75$, $F25$, $F50$ and $F75$, either with or without BESSs, handled by the P2G or the P2P energy sharing policy. The BESS capacity values assigned to REC members correspond to the C_T critical thresholds in the P2P and P2G summer Pareto fronts plotted in Fig. 3, beyond which no significant reduction of G_A is observed.

total energy losses by a variable amount, ranging from 20% to 40%. Quite importantly, minor differences only can be observed between the total relative losses with the P2G and P2P energy sharing policies within the same scenario, although the amount of energy lost in battery charging/discharging and that dissipated over the distribution lines is not the same. This happens because, even if the energy self-sufficiency of REC is higher using the P2P sharing policy than the P2G one, a larger number of power transfers between REC members occur. For example, in scenarios $P75 - F75$, the amount of electrical energy exchanged between REC members in P2P is 1.75 times more than in P2G, while in $P25 - F25$ this ratio is close to 1. In the present case study, the losses over the lines due to electricity distribution are much larger than those due to BESS charging and discharging when BESS penetration is low. However, the difference between such losses decreases as the number of deployed BESSs grows, since larger shares of REC members equipped with a BESS generally cause both a reduction in the amount of electrical energy exchanged between prosumers and an increase in the energy stored into (or drawn from) the BESSs.

6.3. CO_2 emissions

In the present study, the equivalent CO_2 emissions (expressed in tons) are computed by following a standard approach [40], i.e. without involving any life-cycle assessment of PV generators and BESSs. Therefore, just the CO_2 emissions due to the energy $E_G(t_0, T, \mathbf{x})$ absorbed from the main grid through the primary substation in the time interval $[t_0, t_0 + T]$ are taken into account, i.e.,

$$EM_{CO_2}(t_0, T, \mathbf{x}) = k_{CO_2} \cdot E_G(t_0, T, \mathbf{x}) \quad (6)$$

where k_{CO_2} is the electricity-specific emission factor depending on the energy mix of the country (e.g., 0.344 t/MWh in Italy [40]).

Fig. 6 shows a comparison between the total yearly equivalent CO_2 emissions with and without BESSs. Again, the groups of bars in Fig. 6 refer to the six scenarios under study. This analysis reveals that the use of the P2P energy sharing policy reduces emissions by a variable percentage, ranging from 25% to 50% in “present” load conditions and by $10\% - 30\%$ if the energy demand grows due to the widespread diffusion of electrical heat pumps. The CO_2 emissions reduction achieved with the P2G energy sharing policy is still significant but smaller than in the P2P case, as it ranges from −25% in scenario $P75$ to −5% in scenario $F25$. It is interesting to observe that in all cases a broader deployment of BESSs is beneficial in terms of CO_2 emissions.

6.4. An example of investment analysis

The economic profitability of BESS deployment is fundamental in order to assess the feasibility of a REC. However, an in-depth economic investment analysis is a very delicate and complex problem that depends on many parameters, including market-related outlooks and financial issues that are out of the scope of this paper.

In the following, two complementary performance indicators are considered to assess the return of an investment as a function of time, i.e. the Internal Rate of Return (IRR) and the Payback Period (PP). Both indicators rely on an estimation of the so-called Net Present Value (NPV) [41]. If DR represents the average discount rate and Y is the number of years after the initial investment, the IRR and the PP associated with the n-th REC member are defined respectively as

$$\begin{aligned} IRR(x_n, Y) &= \left\{ DR \mid NPV = CAPEX_n + \textstyle\sum_{y=1}^{Y} \frac{MS(y,x_n)}{(1+DR)^y} = 0 \right\} \\ PP(x_n, DR) &= \left\{ Y \mid NPV = CAPEX_n + \textstyle\sum_{y=1}^{Y} \frac{MS(y,x_n)}{(1+DR)^y} = 0 \right\} \end{aligned} \quad (7)$$

where

- $CAPEX_n$ is the CApital EXpenditure (CAPEX) of the n-th REC member for the installation of a PV generator with a BESS of capacity x_n;
- $MS(y, x_n)$ denotes the annual monetary savings achieved in the y-th year, which result from the difference between the prosumer's reduced energy bill (part of the generated energy is either self-consumed or sold) and the energy bill in the purely passive case (i.e., without PV generator and BESS). Possible OPerating EXpenses (OPEX), due for instance to ordinary and extraordinary maintenance activities, may of course reduce the potential savings.

The energy sold to the grid is remunerated at the wholesale market price p_{sell}, while the electricity drawn from the main grid is bought at the retail price p_{buy}, where normally $p_{sell} < p_{buy}$. If the P2G energy sharing policy is used, the difference between p_{sell} and p_{buy} depends external factors driving the market only. In the P2P case instead, the economic value is computed on the basis of the so-called supply-to-demand ratio (SDR) method [23,42]. Following this approach, the energy buying and selling prices between REC members (labelled as $p_{buy,REC}$ and $p_{sell,REC}$, respectively) change dynamically within the REC as a function of the actual demand and supply of energy at a given time. In the current P2P implementation, the energy exchanges between REC

Table 4
IRR and PP values for an aggregator purchasing PV generators and BESSs for all REC members in scenarios $P25$, $P50$, $P75$, $F25$, $F50$ and $F75$ if either the P2G or the P2P energy sharing policy are used.

		P25	P50	P75	F25	F50	F75
IRR [%]	P2G	8	7	5	8	9	11
	P2P	9	7	6	7	9	10
PP [yrs]	P2G	8	10	12	9	9	7
	P2P	8	10	12	9	8	7

members are managed by a single legal entity (shortly referred to as "aggregator" in the following) that has full knowledge of the state of BESSs, PV systems and loads at every time.

In the following analysis, we will assess the return of the investment when the money is spent either by the aggregator or by the REC members themselves. It is worth emphasising that while the expressions in (7) are quite standard and straightforward to use, univocal results of the investment analysis can hardly be obtained due to the multiple parameters and uncertainty sources affecting the NPV computation. Therefore, the results reported in the rest of this Section are just indicative as they rely on the following assumptions, i.e.

- The CAPEX costs are proportional to the peak power of the PV generator (€1200/kWp) and to the BESS capacity (€600/kWh), respectively [43]. The PV and BESS OPEX costs are about 2.1% and 1.5% of their respective CAPEX values per year, as in [43].
- No incentives for PV or BESS deployment are considered (conservative hypothesis).
- The amount of generated PV energy is supposed to decrease linearly by 0.5% per year, due to cells degradation [44].
- If the P2G energy sharing policy is used, the average values of p_{sell} and p_{buy} are set equal to €0.052/kWh and €0.21/kWh respectively, in accordance with the Italian market data in 2019 [45]. On the contrary, when the P2P policy is used, the values of $p_{sell,REC}$ and $p_{buy,REC}$ change as a function of time (see Appendix B), but they remain constrained within the interval [p_{sell}, p_{buy}] to make internal energy exchanges more profitable for REC members, in agreement with the REC core principles in Europe [46].
- To evaluate the IRR, Y is set to 20 years, in line with the typical financial lifetime of PV systems. In order to evaluate the PP instead, DR is assumed to be 0%, as the purpose of this paper is not to compare the profitability of different investments.
- All batteries are replaced after 10 years of use. This is in line with the results of several papers estimating the lifetime expectancy of Lithium-ion stationary home storage systems [47,48].
- Even if the future wholesale electricity prices (and subsequently the retail ones too) are likely to increase throughout Europe [49], the extent of such increments is quite uncertain as it will depend on many factors. For this reason, in the present study those prices are assumed to be constant. Since the economic benefits of installing a PV system with a BESS increase as the gap between the electricity buying and selling prices from/to the grid grows, the assumption of constant electricity tariffs lead to conservative results.
- Again, the BESS capacity values x_n (for $n = 1, \ldots, N$) are those corresponding to the C_T critical thresholds in the P2P and P2G summer Pareto fronts plotted in Fig. 3.

Assuming that the aggregator purchases the assets (see Table 4), there is a sizeable difference between "present" and "future" load scenarios, with the latter ones being more profitable than the former. This is due to the fact that, as a baseline, all users are just consumers. Therefore, if the electricity consumption grows due to a widespread use of electrical heat pumps, the savings due to a higher exploitation of PV generators and BESSs increase as well. Table 4 shows instead a

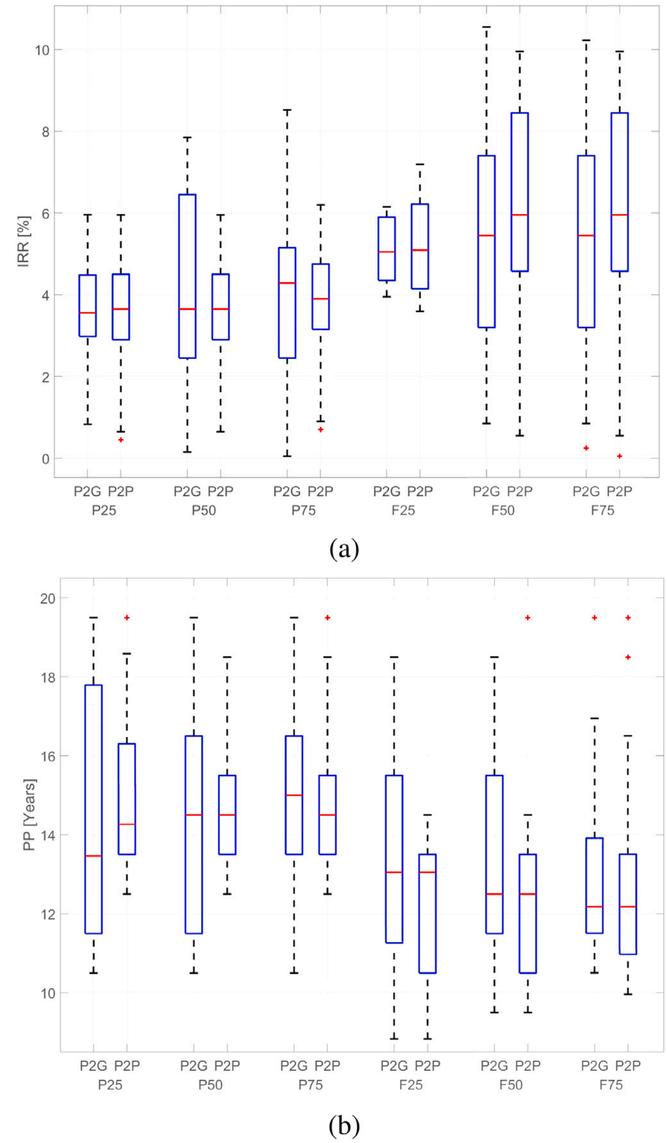

Fig. 7. Box-and-whiskers plots of the IRR (a) and PP (b) values of individual REC members purchasing a PV generator with a BESS in different scenarios by using either the P2G or the P2P energy sharing policy. In practice, only the results related to the REC members with $PP \leq 20$ and $IRR \geq 0\%$ are represented here, i.e. the vast majority.

very small difference between the IRR and PP values obtained by using the P2G and the P2P energy sharing policies. This happens because the main economic driver in the installation of this kind of systems is the PV unit, whose generation capability does not depend on the adopted energy sharing policy. The increase in the number of deployed BESSs has a negative impact on PP and IRR values in the "present" load scenarios without heat pumps (i.e., $P25$, $P50$ and $P75$) and a slightly positive one in the "future" ones with heat pumps (i.e., $F25$, $F50$ and $F75$), thus showing the importance of deploying more BESSs when the energy demand grows.

The box-and-whiskers plots of the individual IRR and PP values associated with the REC members' for which $PP \leq 20$ (which is a standard threshold) and $IRR \geq 0\%$ are shown in Fig. 7(a) and 7(b), respectively. Such results partly confirm those already shown in Table 4, although a non-negligible share of REC members (i.e., up to 15%) may not reach payback within 20 years. In particular, if we switch from "present" to "future" load scenarios, the IRR median values for the same energy sharing policy tend to grow by about 1.5%–2% on average, while dually the PP values decrease by about a variable amount ranging from 1 to 2 years. The share of REC members deploying a BESS does not strongly affect the median values of both performance indicators, but it has contrasting effects on the variability of IRR and PP. Quite interestingly, the IRR and PP interquartile ranges in the P2P case are narrower than in the P2G case in almost all scenarios. This means that the economic benefit of installing a PV unit with a BESS by using a P2P policy is more equally spread among REC members than in the P2G case. This result is in line with the principle underlying the P2P policy, as REC members are supposed to trade power directly between themselves rather than relying on the distribution grid.

7. Conclusions

The expected forthcoming diffusion of Renewable Energy Communities (RECs), especially in the EU, poses several questions on their actual energy, environmental and economic profitability, especially when Battery Energy Storage Systems (BESSs) are used to either store the energy surplus generated by distributed energy resources or supply the residual buildings energy demand. Usually, the optimal BESS sizing and siting problem is formulated and solved from the perspective of Distribution System Operators (DSOs), that are mainly interested in both voltage stability and power flow optimisation. This paper addresses the BESS sizing problem with a prosumer-driven perspective instead, in order to maximise the self-sufficiency of the whole REC while minimising the overall capacity of the BESSs assigned only to the REC members willing to purchase one. On the other hand, the chosen objective functions purposely do not include cost parameters that are sensitive to technology aspects, thus making the qualitative conclusions rather general. The optimisation problem also keeps the risk of over- and under-voltages (due to time-varying load and photovoltaic (PV) generation conditions) under control, thus avoiding curtailments of the power generated by the REC members' by the DSO. The performance of the proposed optimisation strategy was analysed by increasing the yearly power and energy demand (and consequently the peak power of distributed PV generators), the fraction of prosumers accepting to install a BESS and the energy sharing policy between REC members. The optimisation results on a meaningful case study reveal that in each scenario a seasonal threshold BESS capacity configuration exists beyond which the self-sufficiency of the REC does not improve significantly. The share of energy absorbed from the main grid may decrease by a value ranging from about 5% up to about 80% compared to the case when the PV generators are used without BESSs. Such a reduction depends on the season of the year, the energy sharing policy, the number of prosumers installing a BESS and the load conditions. In general, the peer-to-peer (P2P) sharing policy is able to exploit the energy stored in the batteries better than the classic peer-to-grid (P2G) policy, especially when the load energy demand grows and not all of the REC members decide to install a BESS. The P2P-induced profitability improvement is also confirmed by the results of a simplified investment analysis, although a detailed study around this point requires further work. Moreover, the proposed optimal BESS sizing strategy may significantly reduce both the energy losses (by about 20 to 40% in the considered case studies) and the CO_2 emissions with respect to the case without storage (e.g., between 10% to 50%). While the reduction of losses is quite independent of the adopted energy sharing policy, the CO_2 emissions are lower if a P2P policy is chosen.

CRediT authorship contribution statement

Mattia Secchi: Conceptualization, Methodology, Formal analysis, Validation, Software, Writing - original draft. **Grazia Barchi:** Conceptualization, Methodology, Validation, Writing - review & editing, Supervision. **David Macii:** Conceptualization, Methodology, Formal analysis, Validation, Writing - original draft. **David Moser:** Validation, Writing - review & editing. **Dario Petri:** Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. P2G and P2P energy sharing policies

The P2G sharing approach relies on the following basic rules:

1. the instantaneous local PV generation and load consumption values are compared to determine if the battery has to be charged (overproduction) or discharged (underproduction);
2. In the former case, the available PV power is charged into the BESS till reaching the maximum State of Charge (SOC). Once reached, the surplus power is injected into the grid and handled directly by the DSO.
3. In the case of PV power local underproduction, the missing power is first taken from the BESSs till reaching the minimum SOC level. Once the stored energy is over, the power missing at a given time is drawn from the main distribution grid.

This power sharing policy is quite standard and simple to implement as it does not require a dedicated monitoring and distribution infrastructure.

The main rules underlying the P2P sharing policy are instead summarised below.

1. The instantaneous PV production and load consumption values are aggregated to compute the difference between power supply and demand for the whole REC.
2. The available BESSs try to cover the residual power demand/production at a given time on the basis of their SOC.
   - In the case of a local overproduction of PV power, the surplus is charged into multiple BESSs proportionally to their instantaneous Depth of Discharge (DOD). This way, the BESSs with the highest DOD values are charged more than the others.
   - In the case of a PV power local underproduction, the missing power is taken from multiple BESSs, proportionally to their SOC. Hence, the BESSs with the highest SOC values are discharged more than the others.

The P2P sharing policy is more difficult and expensive to implement as it requires a communication infrastructure and an aggregator with full knowledge of the power supply and demand situation and the BESS state of charge of all REC members.

Appendix B. Dynamic energy price computation based on the SDR method

As already introduced in Section 6.4 and in Appendix A, the adopted P2P energy sharing policy relies on the assumption that a single aggregator for the whole REC trades the energy with an electricity retailer.

Let $SDR(t) = \frac{\Delta E_S(t)}{\Delta E_B(t)}$ be the supply-to-demand ratio within the REC at time t [23,42], namely the ratio between the total energy sold and bought by all REC members (denoted with symbols $\Delta E_S(t)$ and $\Delta E_B(t)$, respectively) within a given time slot (e.g., 15 min in the case study at hand). Starting from the basic economic principle that the selling price of any good is inversely proportional to its availability on the market, the electricity selling price within the REC is given by

$$p_{sell,REC}(t) = \frac{1}{a \cdot SDR(t) + b} \tag{B.1}$$

where, in the case at hand, parameters a and b can be determined under two specific conditions, i.e. when $SDR(t) = 0$ and when $SDR(t) = 1$. In the former case, all of the energy required by the REC must be bought from the main grid at a price p_{buy} through the aggregator. Therefore, the buying price within the REC $p_{buy,REC}$ is equal to p_{buy} and must be in turn equal to the internal selling price, since the aggregator should not generate net incomes. Hence, for $SDR(t) = 0$, $b = \frac{1}{p_{buy}}$.

If $SDR(t) \geq 1$ the energy balance of the REC is positive and the surplus of energy can be injected into the grid at a price p_{sell}. Thus, also the internal selling and buying prices between REC members can be set to the same minimum allowed value, i.e. p_{sell}. In particular, if $SDR(t) = 1$, it follows from (B.1) that $b = \frac{1}{p_{sell}}$ and $a = \frac{p_{buy} - p_{sell}}{p_{buy} \cdot p_{sell}}$. Thus, the electricity selling price within the REC is given by

$$p_{sell,REC}(t) = \begin{cases} \frac{p_{sell} \cdot p_{buy}}{(p_{buy} - p_{sell}) \cdot SDR(t) + p_{sell}} & 0 \leq SDR(t) < 1 \\ p_{sell} & SDR(t) \geq 1 \end{cases} \tag{B.2}$$

The buying price within the REC is based instead on a simple economic balance for $0 \leq SDR(t) < 1$, which is described by the following equation, i.e.

$$\left[\Delta E_B(t) - \Delta E_S(t)\right] \cdot p_{buy} = \Delta E_B(t) \cdot p_{buy,REC}(t) - \Delta E_S(t) \cdot p_{sell,REC}(t) \tag{B.3}$$

Therefore, by replacing the definition of $SDR(t)$ into (B.3) and recalling that if $SDR(t) \geq 1$ the buying price must be equal to p_{sell} for the aforementioned reasons, the result is that

$$p_{buy,REC}(t) = \begin{cases} p_{sell,REC}(t) SDR(t) + p_{buy}(1 - SDR(t)) & 0 \leq SDR(t) < 1 \\ p_{sell} & SDR(t) \geq 1 \end{cases} \tag{B.4}$$

Eqs. (B.2) and (B.4) are finally used to determine the monetary savings needed to compute (7).

References

[1] International Energy Agency. Market report series: Renewables 2019. Tech. rep., International Energy Agency; 2019.

[2] Barchi G, Pierro M, Moser D. Predictive energy control strategy for peak shaving and shifting using BESS and PV generation applied to the retail sector. Electronics 2019;8(5). http://dx.doi.org/10.3390/electronics8050526.

[3] Vonsien S, Madlener R. Li-ion battery storage in private households with PV systems: Analyzing the economic impacts of battery aging and pooling. J Energy Storage 2020;29:101407. http://dx.doi.org/10.1016/j.est.2020.101407.

[4] European Parliament. Directive 2018/2001 on the promotion of the use of energy from renewable sources. Off J Eur Union 2018;2018(L 328):82–209.

[5] Müller SC, Welpe IM. Sharing electricity storage at the community level: An empirical analysis of potential business models and barriers. Energy Policy 2018;118(April):492–503. http://dx.doi.org/10.1016/j.enpol.2018.03.064.

[6] Tushar W, Saha TK, Yuen C, Smith D, Poor HV. Peer-to-peer trading in electricity networks: An overview. IEEE Trans Smart Grid 2020;11(4):3185–200. http://dx.doi.org/10.1109/tsg.2020.2969657, arXiv:2001.06882.

[7] Deb K, Agrawal S, Pratap A, Meyarivan T. A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II. In: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 1917, Springer, Berlin, Heidelberg; 2000, p. 849–58. http://dx.doi.org/10.1007/3-540-45356-3_83.

[8] Rodrigues DL, Ye X, Xia X, Zhu B. Battery energy storage sizing optimisation for different ownership structures in a peer-to-peer energy sharing community. Appl Energy 2020;262(January):114498. http://dx.doi.org/10.1016/j.apenergy.2020.114498.

[9] Mazza A, Mirtaheri H, Chicco G, Russo A, Fantino M. Location and sizing of battery energy storage units in low voltage distribution networks. Energies 2019;13(1):2–5. http://dx.doi.org/10.3390/en13010052.

[10] Jannesar MR, Sedighi A, Savaghebi M, Guerrero JM. Optimal placement, sizing, and daily charge/discharge of battery energy storage in low voltage distribution network with high photovoltaic penetration. Appl Energy 2018;226(May):957–66. http://dx.doi.org/10.1016/j.apenergy.2018.06.036.

[11] Babacan O, Torre W, Kleissl J. Siting and sizing of distributed energy storage to mitigate voltage impact by solar PV in distribution systems. Sol Energy 2017;146:199–208. http://dx.doi.org/10.1016/j.solener.2017.02.047.

[12] Khaboot N, Chatthaworn R, Siritaratiwat A, Surawanitkun C, Khunkitti P. Increasing PV penetration level in low voltage distribution system using optimal installation and operation of battery energy storage. Cogent Eng 2019;6(1):1–19. http://dx.doi.org/10.1080/23311916.2019.1641911.

[13] Chen M, Zou G, Jin X, Yao Z, Liu Y, Yin H. Optimal allocation method on distributed energy storage system in active distribution network. In: Energy procedia, vol. 141. Elsevier Ltd; 2017, p. 525–31. http://dx.doi.org/10.1016/j.egypro.2017.11.070.

[14] Zheng Y, Dong ZY, Luo FJ, Meng K, Qiu J, Wong KP. Optimal allocation of energy storage system for risk mitigation of discos with high renewable penetrations. IEEE Trans Power Syst 2014;29(1):212–20. http://dx.doi.org/10.1109/TPWRS.2013.2278850.

[15] Zhang Y, Dong ZY, Luo F, Zheng Y, Meng K, Wong KP. Optimal allocation of battery energy storage systems in distribution networks with high wind power penetration. IET Renew Power Gener 2016;10(8):1105–13. http://dx.doi.org/10.1049/iet-rpg.2015.0542.

[16] Daghi M, Sedghi M, Ahmadian A, Aliakbar-Golkar M. Factor analysis based optimal storage planning in active distribution network considering different battery technologies. Appl Energy 2016;183:456–69. http://dx.doi.org/10.1016/j.apenergy.2016.08.190.

[17] Sardi J, Mithulananthan N, Hung DQ. Strategic allocation of community energy storage in a residential system with rooftop PV units. Appl Energy 2017;206:159–71. http://dx.doi.org/10.1016/j.apenergy.2017.08.186.

[18] Giannitrapani A, Paoletti S, Vicino A, Zarrilli D. Optimal allocation of energy storage systems for voltage control in LV distribution networks. IEEE Trans Smart Grid 2017;8(6):2859–70. http://dx.doi.org/10.1109/TSG.2016.2602480.

[19] Xiao J, Zhang Z, Bai L, Liang H. Determination of the optimal installation site and capacity of battery energy storage system in distribution network integrated with distributed generation. IET Gener Transm Distribution 2016;10(3):601–7. http://dx.doi.org/10.1049/iet-gtd.2015.0130.

[20] Saboori H, Hemmati R, Jirdehi MA. Reliability improvement in radial electrical distribution network by optimal planning of energy storage systems. Energy 2015;93:2299–312. http://dx.doi.org/10.1016/j.energy.2015.10.125.

[21] Liu W, Niu S, Xu H. Optimal planning of battery energy storage considering reliability benefit and operation strategy in active distribution system. J Mod Power Syst Clean Energy 2017;5(2):177–86. http://dx.doi.org/10.1007/s40565-016-0197-4.

[22] Corrá M, Fusari E, Ferrari A, Macii D. A system based on IoT platforms and occupancy monitoring for energy-efficient HVAC management. In: 2019 IEEE 5th international forum on research and technology for society and industry (RTSI); 2019. p. 347–52.

[23] Long C, Wu J, Zhou Y, Jenkins N. Peer-to-peer energy sharing through a two-stage aggregated battery control in a community microgrid. Appl Energy 2018;226:261–76. http://dx.doi.org/10.1016/j.apenergy.2018.05.097.

[24] Secchi M, Barchi G. Peer-to-peer electricity sharing: Maximising PV self-consumption through BESS control strategies. In: Proceedings - 2019 IEEE international conference on environment and electrical engineering and 2019 IEEE industrial and commercial power systems Europe, EEEIC/I and CPS Europe 2019, vol. 1042; 2019. p. 0–5. http://dx.doi.org/10.1109/EEEIC.2019.8783608.

[25] Azzolini JA, Reno MJ, Montenegro D, Azzolini JA, Reno MJ, Montenegro D, Azzolini JA, Reno MJ, Montenegro D. Implementation of temporal parallelization for rapid quasi-static time-series (QSTS) simulations. In: Conference record of the IEEE photovoltaic specialists conference. Institute of Electrical and Electronics Engineers Inc.; 2019, p. 2942–9. http://dx.doi.org/10.1109/PVSC40753.2019.8980591.

[26] Pflugradt N. Load profile generator v9.5.

[27] ASTAT - Istituto Provinciale di Statistica. Dati demografici provincia autonoma di Bolzano, 2018.

[28] Ramos A, Chatzopoulou MA, Guarracino I, Freeman J, Markides CN. Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment. Energy Convers Manage 2017;150:838–50. http://dx.doi.org/10.1016/j.enconman.2017.03.024.

[29] Dipasquale C, Fedrizzi R, Bellini A, Gustafsson M, Ochs F, Bales C. Database of energy, environmental and economic indicators of renovation packages for European residential buildings. Energy Build 2019;203:109427. http://dx.doi.org/10.1016/j.enbuild.2019.109427.
[30] EPRI. OpenDSS PVSystem element model.
[31] Rath K, French RH, Curran A, Khalilnejad A, Lindig S, Moser D. IEA PVPS Task 13-ST2.5: PLR determination benchmark study. 2020, http://dx.doi.org/10.17605/OSF.IO/YN5DE.
[32] Luthander R, Widén J, Nilsson D, Palm J. Photovoltaic self-consumption in buildings: A review. Appl Energy 2015;142:80–94. http://dx.doi.org/10.1016/J.APENERGY.2014.12.028.
[33] Quoilin S, Kavvadias K, Mercier A, Pappone I, Zucker A. Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. Appl Energy 2016;182:58–67. http://dx.doi.org/10.1016/J.APENERGY.2016.08.077.
[34] Wang J, Zhong H, Wu C, Du E, Xia Q, Kang C. Incentivizing distributed energy resource aggregation in energy and capacity markets: An energy sharing scheme and mechanism design. Appl Energy 2019;252(September 2018):113471. http://dx.doi.org/10.1016/j.apenergy.2019.113471.
[35] Alnaser SW, Althaher SZ, Long C, Zhou Y, Wu J. Residential community with PV and batteries: Reserve provision under grid constraints. Int J Electr Power Energy Syst 2020;119(February):105856. http://dx.doi.org/10.1016/j.ijepes.2020.105856.
[36] SunWatts. Modular solar battery cells catalogue.
[37] Voltage characteristics of electricity supplied by public electricity distribution networks; 2010.
[38] Pití A, Verticale G, Rottondi C, Capone A, Lo Schiavo L. The role of smart meters in enabling real-time energy services for households: The Italian case. Energies 2017;10:199. http://dx.doi.org/10.3390/en10020199.
[39] Li X, Hui D, Lai X. Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations. IEEE Trans Sustain Energy 2013;4(2):464–73. http://dx.doi.org/10.1109/TSTE.2013.2247428.
[40] Koffi B, Cerutti A, Duerr M, Iancu A, Kona A, Janssens-Maenhout G. Council of mayors default emission factors for the member states of the European Union Dataset. European Commission, Joint Research Centre (JRC); 2017. p. 13.
[41] Žižlavský O. Net present value approach: Method for economic assessment of innovation projects. Procedia - Soc. Behav. Sci. 2014;156:506–12. http://dx.doi.org/10.1016/j.sbspro.2014.11.230.
[42] Liu N, Yu X, Wang C, Li C, Ma L, Lei J. Energy-sharing model with price-based demand response for microgrids of peer-to-peer prosumers. IEEE Trans Power Syst 2017;32(5):3569–83. http://dx.doi.org/10.1109/TPWRS.2017.2649558.
[43] Prina MG, Lionetti M, Manzolini G, Sparber W, Moser D. Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning. Appl Energy 2019;235:356–68. http://dx.doi.org/10.1016/j.apenergy.2018.10.099.
[44] Lindig S, Moser D, Curran AJ, French RH. Performance loss rates of PV systems of task 13 database. In: Conference record of the IEEE photovoltaic specialists conference. Institute of Electrical and Electronics Engineers Inc.; 2019, p. 1363–7. http://dx.doi.org/10.1109/PVSC40753.2019.8980638.
[45] GME. Italian electricity market prices archive, Gestore Mercato Elettrico.
[46] European Parliament. Directive 2019/944 on common rules for the internal market for electricity. Off J Eur Union 2019;(L 158):18, http://eur-lex.europa.eu/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf.
[47] Farinet D, Maurer M, Vacca L, Spataru SV, Stroe DI. Battery lifetime analysis for residential PV-battery system used to optimize the self consumption - A danish scenario. In: 2019 IEEE energy conversion congress and exposition, ECCE 2019. Institute of Electrical and Electronics Engineers Inc.; 2019, p. 6693–8. http://dx.doi.org/10.1109/ECCE.2019.8912280.
[48] Beltran H, Ayuso P, Pérez E. Lifetime expectancy of Li-ion batteries used for residential solar storage. Energies 2020;13(3):568. http://dx.doi.org/10.3390/en13030568.
[49] Panos E, Densing M. The future developments of the electricity prices in view of the implementation of the Paris agreements: Will the current trends prevail, or a reversal is ahead? Energy Econ 2019;84:104476. http://dx.doi.org/10.1016/j.eneco.2019.104476.