Modelling and optimisation of Renewable Energy Communities as multi-energy systems

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***Abstract*—Renewable Energy Communities (RECs) can be a viable mean to enhance distributed generation from Renewable Energy Sources (RES). RECs are characterised by the presence of multiple "hubs" that produce, consume, and exchange energy. Since RES production is mostly intermittent, a great coordination with demand is needed. Storage solutions can partly overcome time-mismatching between production and demand. Moreover, coupling of different energy carriers (e.g., electricity and heat) can be a way to further exploit RES generation. In this view, RECs can be modelled as multi-node-multi-energy systems (MNMES). However, all the elements above make these systems complex to manage and assess, also due to uncertainty in RES generation, energy prices and end users' demand. Hence, techniques to manage and optimise these new energy systems must be explored, at planning and operational phases, to properly assess their energy, environmental and economic performances while considering technical and regulatory constraints. Consequently, a modelling framework of RECs as MNMES systems is needed to: assess the real performances of RECs; optimally design case studies; explore the use of different technologies and energy carriers; test and compare different optimisation techniques. In this context, techniques from computational intelligence can play a relevant role in pre-processing and using data about RES production, end user demand, energy prices in an intelligent way.**

DISCLAIMER

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I. INTRODUCTION

The two European directives EU 2018/2001[1] (RED II) and EU 2019/944[2] (IEM) addressed the role that citizens can play in the so-called "energy transition" process, by formally acknowledging Energy Communities (RECs) and collective self-consumption. These should represent a valuable mean to boost the spread Renewable Energy Sources (RES) in many energy end uses. The enabling factor for increased production and consumption from RES is the underlying concept of *energy sharing*. This allows indeed to better exploit self-produced energy through increased local consumption and opens up to self-consumption in context where it has been strongly limited until now (e.g. cities where population mostly lives in multi-apartment buildings).

The introduction energy sharing into the Italian regulation has started in 2020 and is still an ongoing process. Even though the current regulation is focused only on electricity [1], sector coupling can be a viable means to further exploit local RES-production. RECs can indeed be thought as an ensemble of individual nodes, each of which satisfies its energy needs by means of a collection of renewable installations, storage systems and coupling components (e.g., heat pumps). Surplus electrical energy can be injected into the public distribution grid and shared with other members of the community. In this context, the modelling of REC becomes crucial for the planning and management of such energy systems. In particular, an appropriate model of these system should consider aspects as the intermittent RES production and the presence of storage solutions, which increase the system's flexibility but also the complexity of the problem.

II. OVERVIEW OF ENERGY SHARING IN ITALY

In 2020 the Italian government started the path towards the transposition of the two European directives with a series of laws that defined a regulatory framework for collective self-consumption and energy sharing. In short, these laws provided: the basic definitions and provisions[3]; the main regulatory aspects[4]; the incentives structure[5]; the technical and operative rules[6]. The initial phase has ended in November 2021, with the full transposition of the European directives into national

[1] European Parliament, Directive (EU) 2018/2001 [...] on the promotion of the use of energy from renewable sources. Available at https://eur-lex.europa.eu

[2] European Parliament, Directive (EU) 2019/944 [...] on common rules for the internal market for electricity. Available at https://eur-lex.europa.eu

[3] Governo Italiano, Legge 28/02/2020 n.8. Available at https://www.gazzettaufficiale.it. [In Italian].

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[6] GSE, Regole tecniche per l'accesso al servizio di valorizzazione e incentivazione dell'energia elettrica condivisa. Available at https://www.gse.it. [In Italian].

law[7]. However, implementing decrees by the national authority (ARERA) are still missing and far-behind schedule.

In the current Italian regulation, energy can be shared within groups of jointly-acting renewable self-consumers (JARSC) and Renewable Energy Communities (RECs). These are legal entities composed of electricity end users: citizens, local authorities, Small-to-Medium Enterprises (SMEs) and other public or private entities. REC members can collectively own and manage renewable generation assets (currently, smaller than 200 kW[8]), and hence produce energy for their own consumption.

A. From one-to-one to many-to-many

While privates producing and self-consuming energy have been existing for years, RECs' great addition lays in the "collective" aspect. Indeed, apart from few exceptions (mainly, long-established energy cooperatives), any scheme introduced in the past for self-production and self-consumption of electricity involved only one producer and one consumer [2]. Collective self-consumption and energy sharing differ from this practice (which can be regarded as individual self-consumption) as they involve one or many producers and many consumers. Thus, energy produced by some members of the REC can be consumed by other members. This can increase local consumption of the self-produced energy, which is indeed the main focus of RECs, differently from other schemes for individual self-consumption. For example, the net billing scheme known as *"scambio sul posto"*, allows [individual] self-consumers to use the distribution grid as a sort of virtual storage. According to this scheme, overproduction (i.e. energy that is produced and not consumed on site), that is injected into the grid, economically compensates the energy bought from the grid. In RECs, instead, energy must be shared instantaneously, or through physical storage systems.

B. Virtual energy sharing

In the Italian regulation, a virtual scheme has been created for the sharing of electricity. Thus, all end users in a REC, as well as the production plants, are connected to the same distribution grid. All the renewable energy produced within the REC (or part of it, if there is on-site consumption) is injected into the grid. Similarly, end users withdraw electricity from the grid and maintain their supply contract. When electricity is simultaneously injected and withdrawn into/from the grid by members of the REC, it is considered to be shared. Therefore, electricity is shared through the [public] distribution grid. Consequently, shared electric energy is defined as the minimum, in each hourly time step, between the sum of the total injections and withdrawals into/from the grid of the end users present in the REC [3]. It should be noted that this concept of shared energy is a purely accounting matter. Indeed, since energy is exchanged through the existing distribution grid, there is no way to assess whether the energy injected is actually consumed by the RECs members. However, given their proximity to the generation plants, it can be assumed that shared energy is consumed within the REC's boundaries.

C. Collective self-consumption and energy communities

Jointly-acting renewable self-consumers are a specific case of electricity sharing. In this case, all the end users are located in the same building or apartment block. Fig. 1, shows a scheme for collective self-consumption in a multi-family residential building. A collectively-owned photovoltsic system is installed on the building's rooftop. Electricity generation can be consumed on-site for shared services (e.g., elevator, lighting of common spaces) or injected into the grid. The household users in the building can use this injected energy to fulfill their own electricity demand, thus sharing it. Injected energy that is not shared is then exchanged with the national electricity grid. Similarly, electricity demand (both on-site and virtual) that cannot be fulfilled using local RES generation is taken from the national grid.

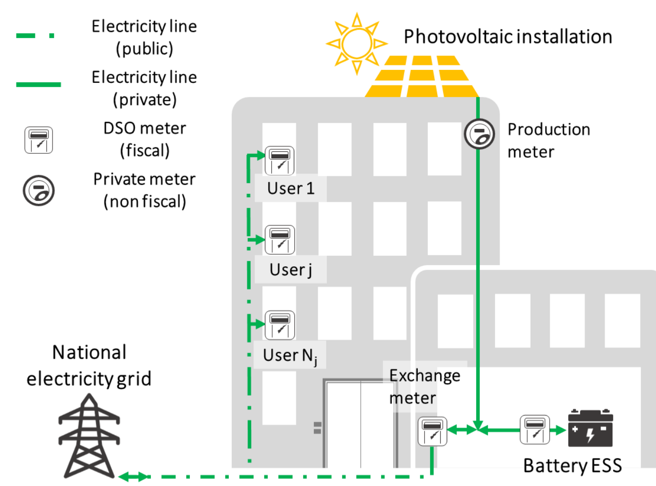


Fig. 1. Example of collective self-consumption in a residential building. [Adapted from [1]].

RECs reproduce the same concept but on a wider scale. Indeed, end users located in different buildings can take part to a REC, as long as they are connected to the same low-voltage (LV) distribution grid[9]. For example, Fig. 2 shows a simple example of a REC, where different types of members (produced, consumer, prosumer) are connected by and exchange energy through the same distribution grid.

D. Economical regulation

Shared energy decreases the REC' exchanges with the national grid, since it is consumed within its boundaries. Thus, energy sharing reduces the energy flows in the national

[7]Governo Italiano, Decreti Legislativi 8 novembre 2021, n.199, available at https://pdc.mite.gov.it and n. 210, available at https://www.gazzettaufficiale.it. [In Italian].

[8]This limit, that holds on the single installation, should be extended to 1 MW in the new regulation.

[9]This limit should be extended to the same medium-voltage (MV) distribution grid with the new regulation

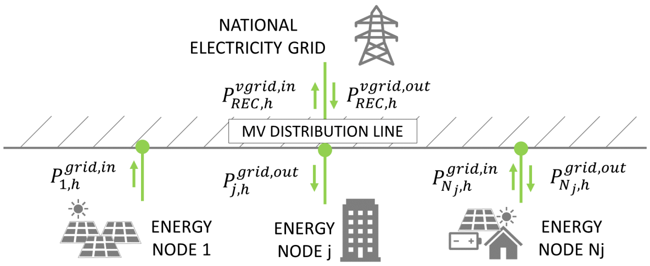


Fig. 2. Basic scheme of a REC with different types of members. [Source [4]]

transmission and distribution grid. Therefore, the current regulation economically recognises electricity sharing in RECs. Globally, the economical value of shared energy in RECs can be considered roughly equal to 120 €/MWh. Moreover, all electricity injected into the grid (i.e. all the PV production that is not consumed on-site) can benefit from the dedicated withdrawal service, known as *ritiro dedicato*. This recognises injected electricity at the hourly zonal market price, generally lower than the retail price. On the other side, all electricity withdrawn from the grid is still purchased by the users from the suppliers at retail price.

III. RECs AS MULTI-NODE, MULTI-ENERGY SYSTEMS

The key point of a REC is the possibility for its members to share electricity between each other. RECs members can hence be considered as energy nodes (see Fig. 2), that exchange electricity harnessing the portion of the distribution grid to which they are connected. In particular, electricity is *shared* when it is injected into the grid by an energy node and *simultaneously* withdrawn by other nodes in the REC. With respect to the scheme presented in Fig. 2, shared energy can be calculated as follows:

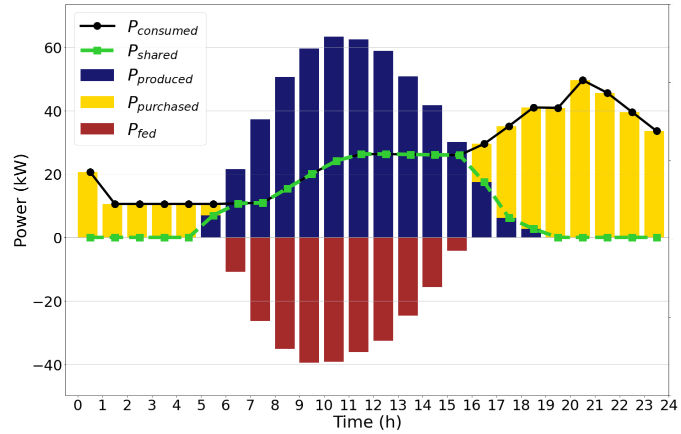
$$E_{REC,h}^{shared} = \min\left(\sum_{j\in J} P_{j,h}^{grid,in}\Delta t_h; \sum_{j\in J} P_{j,h}^{grid,out}\Delta t_h\right), \quad (1)$$

where $P_{j,h}^{grid,in}$ and $P_{j,h}^{grid,out}$ are, respectively, the grid injections and withdrawals of user j in time step h of length Δt_h (namely, one hour); J is the set of users in the configuration.

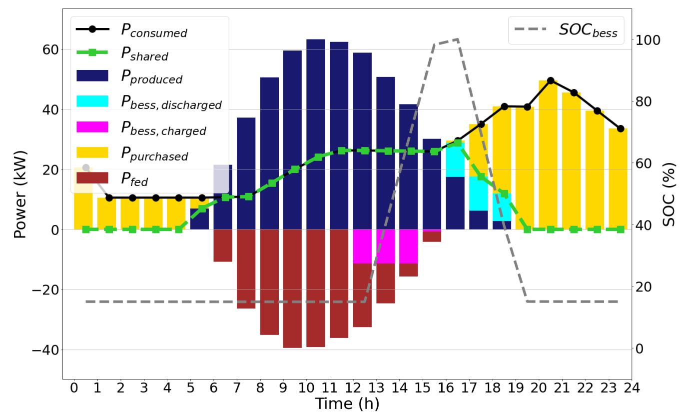
A. Storage systems

The most widespread RES in the residential sector and in RECs is photovoltaic (PV) [1], [5]. Being it intermittent, its production exhibit a pattern during the day that cannot be controlled as it depends on meteorological parameters. End users' consumption also follows a certain pattern during the day. For instance, Fig. 3a shows typical hourly production and consumption patterns during one day in a PV-based residential REC. While the total energy consumption and production during the day may be comparable, the latter is only partly shared, due to mismatching patterns between demand and VRES production.

Different strategies can be adopted to overcome this issue. One solution is represented by storage systems, which can



(a)



(b)

Fig. 3. Hourly production and consumption profiles in a REC (a), and energy flows in presence of a storage system (b).

be effectively used to increase shared energy in a REC, as shown in Fig. 3b. However, while providing flexibility, storage systems increase the complexity of the system. As different variables may affect the storage systems utilisation (e.g., consumption, energy price, etc.), optimal management strategies are required to maximise their exploitation.

B. Sectors coupling

Fig. 4 compares the monthly production from a PV system to the end users' electricity consumption. The two quantities are strongly mismatching. For instance, during summer months, a large part of the PV production could not be shared even if short-term storage solutions compensated hourly variations. Beside considering medium-long term storage systems, one solution could be electrification of the cooling demand. Also in the case of cooling (or heating) demand, short-term [thermal energy] storage systems can be considered within each energy node, to decouple RES availability from end users' demand.

Currently, energy exchanges between REC nodes only involve electricity. However, other energy vectors can be considered "locally", i.e. within a single energy node. In this view, each energy node in the REC can [potentially]

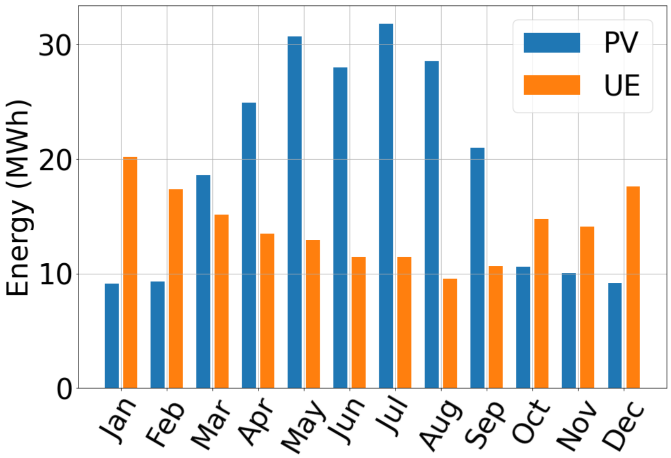


Fig. 4. Monthly photovoltaic production (PV) and end users electricity consumption (UE) in a REC.

be a multi-energy system. Production of energy vectors other than electricity, however, must be consumed within a node's boundaries, since there are no rules for injecting energy in distribution networks apart from the electricity grid. Nevertheless, different energy carriers can be coupled with electricity thanks to the presence of conversion units (e.g. heat pumps). Thus, sectors coupling opens up to interesting possibilities for increasing self-consumption of locally-produced renewable electricity (both on site and virtually, i.e. through sharing), by electrifying other energy needs.

In order to properly explore such possibilities for RECs, sectors coupling must be considered when modelling energy nodes. In this view, RECs can be considered as multi-nodes energy systems, where each node is an arbitrarily complex multi-energy system. For instance, Fig. 5 depicts a possible scheme for an energy node where local demand of three types (electricity, heating, cooling) is satisfied by means of a collection of production, conversion and storage technologies. In addition, the node is connected to and exchanges energy with other (potentially similar) nodes through the electricity distribution grid.

IV. Optimisation and assessment

The complexity of a REC considered as a multi-node multi-energy system (MNMES) requires adequate approaches to manage the energy flows within and between nodes. Indeed, many variables influence the optimal flows, such as the RES production, end users consumption and energy prices (e.g. for the energy that is bought from/injected into the grid). While being true for any multi-energy system, this aspect is particularly important for RECs, where all nodes are interconnected and can exchange electricity. An effective strategy should indeed coordinately manage all the energy nodes in a REC. This way, energy sharing can be considered as a valuable addition to on site consumption from RES (which already reduces the dependence from the national grid).

A. *Optimal energy flows*

The literature on multi-energy systems usually uses mixed-integer-linear-programming (MILP) to find the optimal the optimal energy flows within the system (optimal scheduling). This approach uses simplified (linear, or piece-wise linear) models of the technologies involved. The optimal energy flows in a REC can be found through a MILP problem, considering RES production and end users' consumption as known input parameters and the minimisation of the operative energy costs as objective. However, the computational burden of finding an optimal solution can easily explode with the number of degrees of freedom (especially with binary variables, such as those related to scheduling of units like storage systems). For this reason, a fine time-resolution is not easily achievable. Nonetheless, the adoption of hourly time steps complies with the official definition of shared energy. Moreover, the optimisation problem is usually implemented on a limited time horizon, such as one day or one week.

The optimisation of energy flows is functional both at a planning (design) and operational (online) phase. In the former case, typical days can be identified, in which input parameters are similar. Typical days can then be assumed to be representative of a whole year. Hence, after solving the optimisation problem during typical days, yearly values can be extrapolated. When energy flows are to be optimised online, instead, one possibility is to adopt a sliding window horizon, thus repeating the optimisation at each new time step. This technique falls under the umbrella of model predictive control (MPC).

B. *Performance assessments*

KPIs are used to assess the performances of the REC once it is optimised, generally on a yearly basis. In the planning phase optimal, or nearly-optimal, sizes of the active elements in the REC (production, conversion and storage systems) must be found. When searching the design space, KPIs are used to compare different REC configurations. Three groups of KPIs are considered: energy, environmental and economic. Since the REC's objective is to locally consume the self-produced renewable energy, energy performances can be measured in terms of self-consumption (SC). Self-sufficiency (SS) is instead the ratio of consumption satisfied through local-production over the total consumption. This is also important for RECs, as it measures the autonomy from the external energy grids. Environmental KPIs can be instead the reduction in the REC's in CO_2 emissions with respect to a base-case scenario where the REC's energy needs are completely fulfilled by the external energy grids. Finally, economic performances can be measured by the internal rate of return (IRR) of the initiative. Otherwise, an important measure in the context of RECs can be the percentage cost reduction (PCR) for the consumers. Different KPIs can usually conflict with each other (especially, the environment and economic ones) and cannot be maximised at the same time. The REC's design and assessment hence becomes a multi-objective problem.

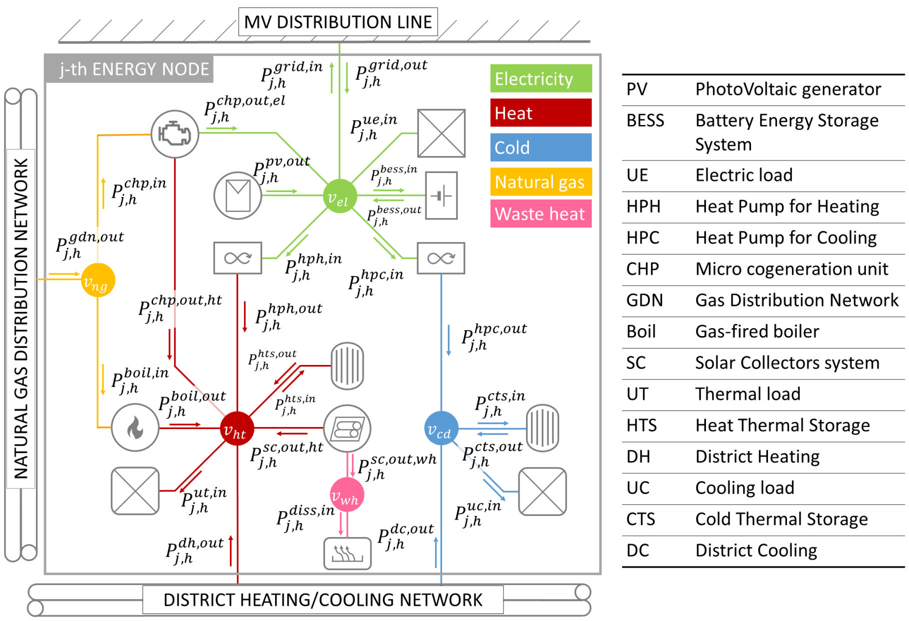


Fig. 5. Scheme of an energy node in a REC, seen as a multi-energy system. [Source [4]].

C. *Some relevant results*

Fig. 6 and 6 provide two simple examples of the application of the previously discussed topics. The first one is about a case study of a REC with multiple nodes, each of which can have PV installations, heat pumps, electricity and heat storage systems (hence, multiple nodes). The figure shows the results of two different energy flows optimisations. On the right plot, nodes in the REC are optimised individually. After optimisation, electricity exchanges between nodes are calculated according to Eq. (1). On the left plot, instead, the nodes are optimised all at once, hence considering the value of shared energy directly in the procedure. The results (for sake of simplicity, only the energy flows during one day are shown) show how coordinated optimisation can strongly increase shared energy (and decrease costs). Of course, the price to pay is the increased complexity of the problem.

The second figure (Fig. 7) is about a case study of residential JARSC and shows the result of its multi-objective sizing. The analysis has been conducted considering one KPI for each category, respectively the SC (energy), the Δ_{CO_2} (environment) and the PCR (economics). In the case study, a multi-house building was considered where end users adopted a PV system coupled with a battery energy storage system (BESS) and an heat pump (HP) coupled with a thermal energy storage system (HTS). The analysis showed that the presence of the HTS allowed to reduce the size of the HP (with respect to the case without storage), by increasing its duty cycle. Moreover, the KPIs showed both the economical and environmental sustainability of the initiative, which could lead to a reduction of more than 50 % of the building's CO_2 emissions (thanks to electrification of heating consumption). However, as previously mentioned, economical and environment KPIs are in conflict, hence they cannot be optimised at the same time, therefore a trade-off solution is to be found.

V. Remarks on Computational Intelligence

Model complexity and the need for a great amount of input data in the analysis and optimisation of RECs as MNMES justifies the adoption of techniques from computational intelligence. These can effectively be used to ”gain knowledge” from available data. For instance, a well-known application is represented by the use of non-linear mappings, such as Artificial Neural Networks (ANN), to predict output quantities, e.g. RES production, from input parameters, such as environmental conditions. Forecasting or prediction of end users demand and energy prices are other examples of these concepts. Clustering techniques (e.g. k-means) can instead be used to extract typical days from yearly time series, in order to reduce the computational burden of the optimisation procedure. Another promising technique is Reinforcement Learning, which can be deployed in the [online] control of energy systems. This is based on one or more agents that are able to ”learn” the dynamics of an environment through iterative interactions with it. As they give an immediate response to the ”state” the environment presents them, based on the previous interactions, these systems are particularly suited for real-time applications [6]. However, despite being promising, preliminary studies on these techniques also show that more research is needed to unlock their actual potential.

Acknowledgment

Prof. Maurizio Repetto, Dr. Paolo Lazzeroni, and Francesco Moraglio contributed to this research with their efforts and ideas.

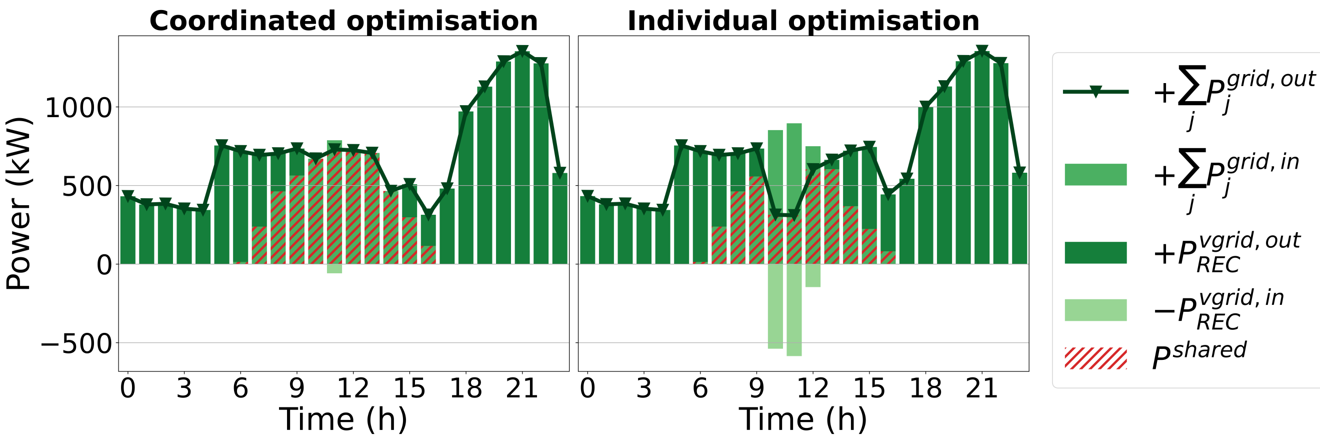


Fig. 6. Individual versus coordinated optimisation of the energy flows in a REC with multiple energy nodes. [Source [4]].

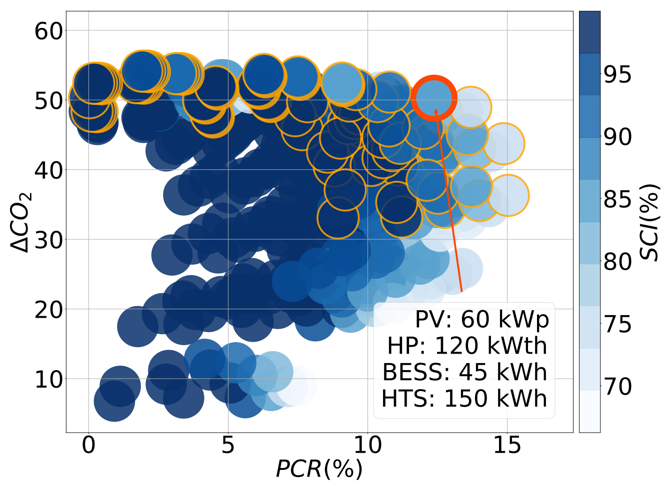


Fig. 7. KPI analysis of a case study of residential JARSC.

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