Modeling of Renewable Energy Communities: the *RECoupled* approach

Paolo Lazzeroni, Gianmarco Lorenti, Francesco Moraglio and Maurizio Repetto
Dipartimento Energia "Galileo Ferraris"
Politecnico di Torino, Torino, Italy
name.surname@polito.it
Corresponding author: Gianmarco Lorenti, gianmarco.lorenti@polito.it

***Abstract*—The increase in energy production and consumption from Renewable Energy Sources (RES) is becoming strategic to reduce CO_2 emissions and to contrast climate-change related issues. In this view, EU promoted the creation of Renewable Energy Communities (RECs) to foster the sharing of local RES production among end users. Even if technological aspects of these energy systems are not critical, their complexity in management and planning is presently arising due to intermittent RES generation and end users demands. Storage solutions can contribute to RES exploitation and to the flexibility of RECs, but introducing further complexity in the system.**

In this context, an adequate model of the physical and management layouts of the REC becomes crucial to perform energy, economic and environmental analyses. Consequently, in this paper a modelling approach of interconnected multi-energy systems named *RECoupled* is proposed to simulate such RECs in the Italian context, taking into account the corresponding rules and peculiarities.

***Index Terms*—Multi-Energy Systems, modelling, simulation, RES, Energy Communities.**

I. Introduction

The concept of Renewable Energy Community (REC) has been recently introduced in the EU regulation (EU Directive 2018/2001, REDII) as well as in the Italian National Law (Decree-Law 162/2019). The latter states that end users can join in RECs to increase the consumption and production of electricity from Renewable Energy Sources (RES). Therefore, members of a REC can share electricity over-generation through the public distribution grid.

In this context, the modelling of REC becomes crucial for the planning and management of such energy systems. In particular, an appropriate surrogate of the physical layout 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. Modelling approaches should be also capable of capturing operational, technical and regulatory limitations. Additionally, even if current REC applications involve mainly electricity [1], other energy vectors can be included .

The literature on the modelling of multi-energy systems is wide and well-established. An extensive review of existing approaches and tools is presented in [2], together with their main characteristics and limitations. Among these is the *open* feature of these tools, which is only rarely guaranteed. Another highly desirable feature is the adoption of optimisation techniques in the simulation of the operations of such complex energy systems. Mixed-Integer-Linear-Programming (MILP) is widely used in these kinds of problems, as it is relatively simple and easily adaptable to many problems [3]. Other relevant elements that characterise modelling approaches are the geographical (from Nation to building-wide) and temporal resolutions (generally hourly or finer), and the coupling of different energy-carriers (e.g. heat and electricity) [4].

Nonetheless, the literature on modelling of RECs as multi-energy systems is rather sparse, due to their relatively recent development. In early stages, rather simple models where adopted, as in [5], where an aggregated electricity demand, a community-owned PV plant and collective storage were considered. In [6] a multiple-node approach is proposed, where users in the REC can have their own PV system, but only a collective storage is present. A multi-node model is also presented in [7] but considering electricity only. A model of REC coupling electric and thermal energy is presented in [8], where a single *active* node is considered. A very recent paper [3] proposes a model of REC with multiple *active* nodes, as well as different energy carriers. Hence, in each node, different generation, conversion and storage technologies can be present.

The presence of multiple electricity storage systems needs particular attention in REC's modelling, as National Laws may set particular requirements on the electricity that can be shared by REC's members (e.g., from RES only). In Italy, for instance, electricity withdrawn from and later re-injected into the grid cannot account as shared energy [9]. Therefore, a modelling approach named `RECoupled` is proposed in this paper to simulate the performances of RECs, tailored on the Italian regulatory framework. In line with the above considerations, REC is modeled as a multi-energy system, composed of multiple nodes, where the energy demand is satisfied by means of a collection of production and conversion units, and storage systems. Surplus of electricity production can be shared with other members of the community through the public distribution grid, while heat generation can only be stored

Preprint submitted to 2022 IEEE 46th Annual Computers, Software, and Applications Conference (COMPSAC), 2022, Los Alamitos, CA, USA Published article at https://doi.org/10.1109/COMPSAC54236.2022.00213.

and locally consumed. Particular attention is given to the modeling of electricity storage systems in order to account for specific regulatory constraints. The model is used to upgrade a previously developed open-source tool [10], which was used in [5]. Also in this case, the source code will be made freely available on GitHub (at https://github.com/cadema-PoliTO).

The rest of the paper is structured as follows. An overview of the structures used to create the REC's model in `RECoupled` is provided in Section II. The physical, technical and operative constraints used in the model are described in detail in Section III, and the results of two applications of `RECoupled` are provided in Section IV. Finally, Conclusions and further developments are discussed in Section V.

II. System Layout

According to [9], RECs are composed of groups of *electric* end users located in the same Medium Voltage (MV) distribution grid. Each end user is identified by a *connection point* with the grid to withdraw and/or inject energy: *active* users (i.e. producers and prosumers) can inject electricity into the grid, while *passive* ones can only withdraw it. A general representation of a REC as an ensemble of different end users (i.e. producer, consumer, prosumer) is provided in Fig. 1. Under a connection point, each user could actually be a multi-energy system where demands of different energy carriers, not only electricity, can be fulfilled by means of a collection of production, conversion and storage technologies. Hence, "*energy node*" is also used here to address an end user in the REC.

`RECoupled` is the proposed approach for the creation of a computer model reflecting the REC structure described above. In this approach, the blocks to build a topological structure of a REC are (user-defined) `Python` classes compliant with the following organisation:

- a `Configuration` is a representation of a REC containing different end users or, equivalently, energy nodes, connected by the same distribution grid;
- a `User` is actually a container for the elements present in an energy node (e.g. generators, conversion units, loads, storage systems,...);
- a `Unit` is in general a representation of an element that can be found in each energy node.

Three main layers can be identified in the architecture of `RECoupled`, as shown in Fig. 2: input data provided to build the model of the REC are stored in the *input* layer; structures representing the REC are in the *internal* layer; finally, results of the simulations are provided in the *output* layer.

Data provided as inputs are `yaml` setup files and `csv` files containing time series of quantities, such as users demands and RES production. To build the internal representation of a REC from these data, firstly a `Configuration` (i.e. a REC) is created, specifying a list of the energy nodes in the REC. Then, for each node a `User` instance is created and added to the REC. In particular, for each `User` instance a setup `user_.yaml` file is imported to specify the elements within the energy node. Finally, these elements are used to create `Unit` instances picked from internal built-in models.

In order to allow the simulation of the same REC under different scenarios, a specific `Simulation` class has been introduced, whose instances are created using the parameters in `sim_config.yaml` file. These parameters are needed for the evaluation of Key Performance Indices (KPIs). Different scenarios may depend not only on the parameters (e.g., economic), but also on the users present in the REC, hence a list of users is part of the `Simulation` attributes.

REC's simulation process consists in optimising the electricity exchanges between end users in the REC, as well as optimising the power flows within each end-user, for all the energy carriers and the technologies involved. Simulation of reference periods can be used in place of a whole year to reduce the computational effort. Nevertheless, yearly output quantities can be extrapolated to calculate KPIs of the REC's performances from energy, environmental and economic point of view.

III. REC Model

The key point of a REC is the possibility of sharing electricity among the users (i.e. the energy nodes of Fig. 1), harnessing the portion of the distribution grid where energy nodes of a

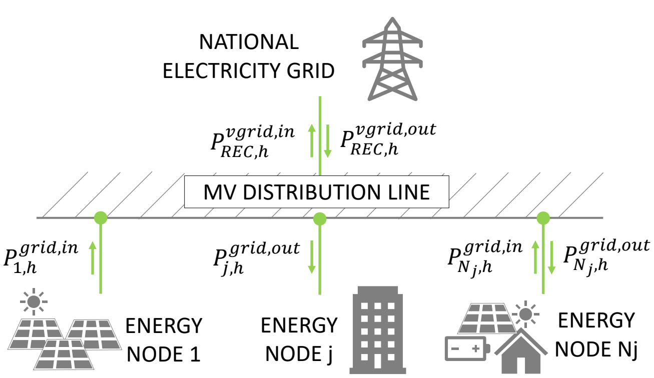


Fig. 1. General representation of REC.

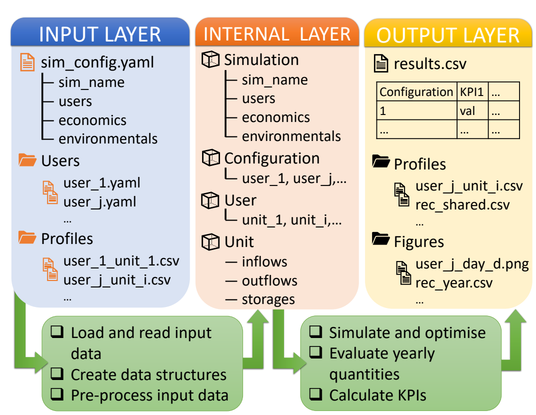


Fig. 2. Outline of `RECoupled` architecture and process layout.

TABLE I
LIST OF VARIABLES

Variable	Quantity
t	Time (h)
P	Power (kW)
E	Energy (kWh)
SOC	State of Charge (-)
η	Efficiency/conversion coefficient (-)
δ	Binary variable

TABLE II
LIST OF SUBSCRIPTS AND SUPERSCRIPTS

Sub/superscript	Meaning
j	Energy node, user
i	Unit, component
v	Energy vector
h	Time step
in	Input power flow
out	Output power flow
stor	Stored quantity

REC are connected. Consequently, shared energy is assumed to be consumed within the REC boundaries, instead of being exchanged with the National grid. 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. Thus, the REC energy balances are based on the electricity exchanges of the energy nodes within the grid.

Differently, "local" balances of other energy vectors must hold inside a single energy node. In particular, production of other energy vectors must be consumed only within a single user's boundaries, since rules for injecting energy in distribution networks are currently not available for energy carriers other than electricity. Nonetheless, different energy carriers can be coupled with electricity thanks to the presence of conversion units (e.g. heat pumps). Therefore, while the energy nodes in the REC may appear as independent systems (complying with their own constraints), they represent a fully-interconnected system and should be analysed in a coordinated way.

The model equations described in the followings are based on the two key concepts of *spatial* and *temporal* resolution. Based on the above considerations, the spatial scale works on two levels at the same time, the REC and the single energy nodes, while *instantaneous* energy balances are considered for the temporal resolution. Nonetheless, when sizing a REC, one hour long time steps can be considered, in accordance with the Italian regulation.

A. REC

Energy nodes in the REC exchange electricity among each other through the public distribution grid, as shown in Fig. 1. In the National regulation, shared energy is defined in each hourly time step *h* as the minimum between the total injections and withdrawals of the users, and it is calculated as follows:

$$E_{REC,h}^{shared} = \min\left(\sum_{j\in J} P_{j,h}^{grid,in}\Delta t_h; \sum_{j\in J} P_{j,h}^{grid,out}\Delta t_h\right), \quad \forall h = 0,\ldots,N_h-1, \quad (1)$$

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; J is the set of users in the configuration.

Shared energy is assumed to be produced/consumed within the REC boundaries, thus reducing the energy flows towards/from the outside of the REC. Indeed, the global energy balance on the distribution grid is defined, as follows:

$$P_{REC,h}^{vgrid,in} - P_{REC,h}^{vgrid,out} = \sum_{j\in J} P_{j,h}^{grid,in} - \sum_{j\in J} P_{j,h}^{grid,out}, \quad \forall h = 0,\ldots,N_h-1, \quad (2)$$

where $P_{REC,h}^{vgrid,in}$ and $P_{REC,h}^{vgrid,out}$ are the electric power exchanged by REC with the National grid (i.e. injections and withdrawals, respectively). These quantities are *virtual*, as there is no real measure in the physical layout.

B. Energy node

Energy sharing currently involves electricity only. Nevertheless, different energy vectors can be considered in the single energy node of the REC. Fig. 3 provides an extensive, yet not necessarily complete, example of multi-energy node. Together with the different technologies, connections with other energy networks, such as natural gas and district heating/cooling, are also considered to fulfill the local energy needs. However, energy sharing on these networks is not presently regulated and self-generation must be consumed locally.

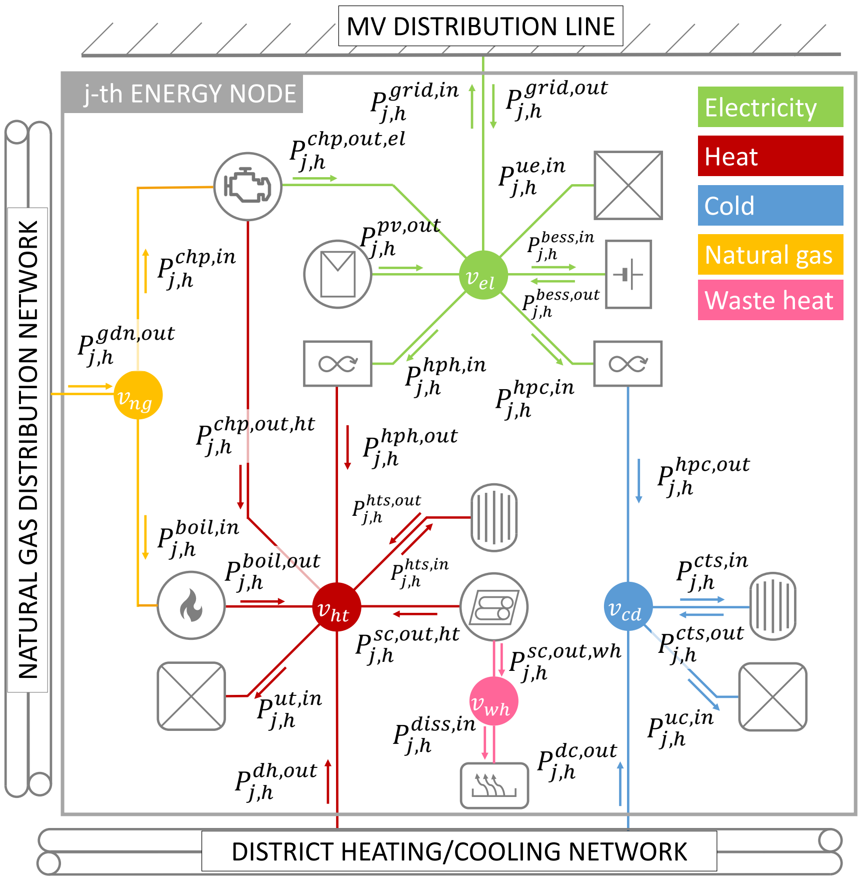
Inside an energy node *j*, a balance equation ensures that the demands are met at all time steps, for each energy vector *v*, as follows:

$$\sum_{i\in I_j^{in,v}} P_{j,h}^{i,in,v} = \sum_{i\in I_j^{out,v}} P_{j,h}^{i,out,v}, \quad \forall h = 0,\ldots,N_h-1, \quad (3)$$

where $P_{j,h}^{i,in,v}$ and $P_{j,h}^{i,out,v}$ are inflow and outflow powers of vector *v* to a unit *i* in the node *j*, respectively; while $I_j^{in,v}$ and $I_j^{out,v}$ are the sets of units which have vector *v* as an inflow and an outflow, respectively. According to (3), all units within an energy node that have a certain energy carrier as an inflow or outflow take part to this balance equation.

C. Units

A general model of unit is implemented to increase the modularity of the approach. Fig. 4 provides a qualitative representation of this model. In general, units have energy inflows, P^{in}, and outflows, P^{out}, which cross the unit boundaries. Clearly, also energy losses due to input and output efficiencies, η^{in} and η^{out} are taken into account.



PV	PhotoVoltaic generator
BESS	Battery Energy Storage System
UE	Electric load
HPH	Heat Pump for Heating
HPC	Heat Pump for Cooling
CHP	Micro cogeneration unit
GDN	Gas Distribution Network
Boil	Gas-fired boiler
SC	Solar Collectors system
UT	Thermal load
HTS	Heat Thermal Storage
DH	District Heating
UC	Cooling load
CTS	Cold Thermal Storage
DC	District Cooling

Fig. 3. Schematic representation of an active energy node with multiple energy vectors.

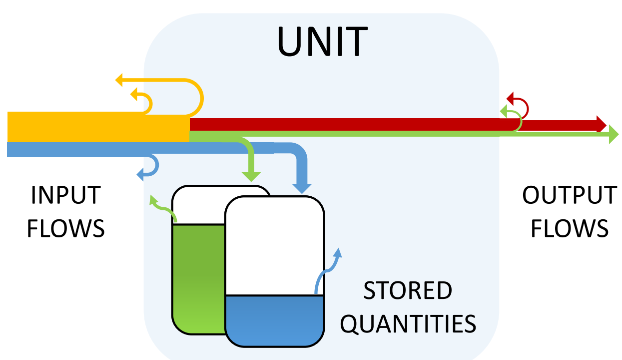


Fig. 4. Qualitative representation of a generic unit.

The energy conversion inside the unit, from an energy vector v' in input to another one v'' in output, is represented by a conversion factor $\eta^{conv,v' \to v''}$. Thus, energy conversion are described by constitutive equations relating the input and the output flows, as follows:

$$\eta^{conv,v' \to v''} P_h^{in,v'} = P_h^{out,v''}, \qquad \forall v' \in V^{in}, v'' \in V^{out}, \quad (4)$$

where V^{in} and V^{out} are the sets of, respectively, the inflows and the outflows of different energy vectors of the unit. The indices related to user j and to unit i are omitted from the notation for the sake of readability. Even when not specified, all equations hold in each time step $h \in [0, N_h)$.

In some cases (i.e. storage unit), a unit can store energy and release it in a different time step. Thus, a storage efficiency, η^{stor}, is considered to account for self-discharge phenomena, while storage capacity provides an upper bound to the stored energy, E^{stor}. The state of charge (SOC) is used to assess the percentage of storage capacity "occupied" at each time step. In these cases, storage systems are described through balance equations between subsequent time steps, h and h', as follows:

$$E_{h'}^{stor,v} - \eta^{stor,v} E_h^{stor,v} = \left(\eta^{in,v} P_h^{in,v} - P_h^{out,v} \frac{1}{\eta^{out,v}} \right) \Delta t_h, \qquad \forall v \in V^{stor}, h = 0, \ldots, N_h - 1 \quad (5)$$

where $h' = h + 1$ in all time steps but the last one, where it is set equal to 0 to impose a periodicity in the storage's SOC of N_h time steps; V^{stor} is the set of energy vectors that can be stored in the unit.

Other operative constraints bound quantities to a minimum and/or maximum value, while logical constraints are used to impose mutual exclusivity between state variables, δ (e.g. related to storage systems charge and discharge phases):

$$\delta_h^{in,v} + \delta_h^{out,v} \leq 1, \tag{6}$$

Particular attention has been devoted to the modeling of battery electric storage systems (BESS) used in REC. Classically, BESS can store RES overproduction within an energy node. In a REC setup, BESS units can also be used to store electricity produced by RES injected by another node, thus increasing the shared energy. Afterwards, the stored electricity can be used locally or re-injected. However, according to the National regulation, users' injections that count for the calculation of the shared energy must be corrected by subtracting the electricity withdrawn from the grid, stored in a BESS and then re-injected [9]. The BESS is hence divided into two fictitious separate subsystems, as in Fig. 5, to properly manage this aspect. A "local" storage *l* accounts for energy stored from local RES generators, i.e. in the same energy node, while a "non-local" one, *nl*, accounts for energy stored from the grid (i.e. injected by other energy nodes).

The input power to the non-local storage, $P_h^{nl,in,el}$, in an electricity storage system is defined as follows:

$$P_h^{nl,in,el} = \min\left(P_h^{in,el}; P_h^{grid,out}\right) \tag{7}$$

where $P_h^{in,el}$ is total the power entering the unit.

Balance equations like (5) are included separately for both subsystems (i.e local and non-local). The input/output powers and the stored energy are the sum of the related local and non-local quantities, so that the whole storage system balance holds. The output power of the non-local storage, $P_h^{nl,out,el}$, is then used to calculate the *incentivable* energy injected by an energy node. The latter is the part of the total injected energy that comes only from local units and is hence evaluated, as follows:

$$P_h^{grid,in,inc} = \max\left(0; P_h^{grid,in} - \sum_{i \in I^{stor,el}} P_h^{i_{nl},out,el}\right) \tag{8}$$

where $I^{stor,el}$ is the set of BESS unit in the energy node.

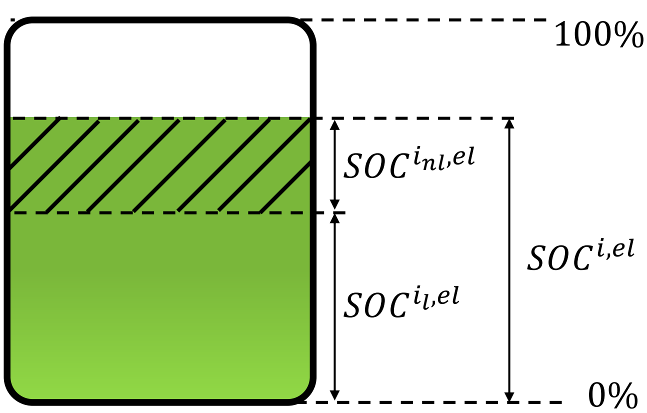


Fig. 5. Electricity storage split into *local* and *non local* subsystems.

The incentivable injected energy replaces the actual injections in the definition of the shared energy proposed in (1), which is then rewritten as follows:

$$E_h^{shared} = \min\left(\sum_j P_{j,h}^{grid,in,inc} \Delta t_h; \sum_j P_{j,h}^{grid,out} \Delta t_h\right) \tag{9}$$

While this approach is tailored on the Italian regulation, it can also be adopted in other situations. For example, when non-RES electricity generators are present (e.g., a gas-fuelled CHP), BESS units can be divided into *renewable* and *non-renewable* subsystems, thus accounting separately for RES-based electricity (that can be shared in a REC) and non-RES.

IV. Case studies

`RECoupled` has been used to simulate a simple REC with only two users, and a larger one of fifty users. In both cases, the users in the REC have the following common features:

- Each user is actually an aggregate of households located in a same multi-family residential building [1];
- Buildings are under the same environmental conditions (solar irradiance and outdoor temperature)
- All users have the same heating and electricity demands.

Users are schematically represented by the energy node in Fig 3, where the electricity and heating loads are, respectively, the aggregated electricity demand of the households and the heating demand of the building. The cooling side is not considered in the analysis, as well as the CHP and SC units. The remaining technologies (PV, BESS, HP, HTS) are assigned to some energy nodes with different installed capacity in order to diversify the set of users. Power flows in the REC are simulated during a reference period of one day, discretised into $\mathrm{N_h} = 24$ time steps. A MILP optimisation problem is generated from the model equations described in Section III using `PuLP` library [11]. The objective is set as the minimisation of the total operative costs. The problem is solved by using `Gurobi` [12]. In line with this work's scope, only the results about the optimised power flows are provided and shown. However, REC's simulation could be repeated over multiple reference days in order to assess the REC's performances in a whole year.

A. REC with two energy nodes

This case study is meant to provide an overview of power flows within single nodes in a REC with the following two energy nodes:

- one with a large PV generator of 90 $\mathrm{kW_p}$, and a small storage capacity available of 24 kWh (User 1);
- one with a larger storage system of 75 kWh, which however can only be charged from the grid (i.e. PV is not present), and a increased electricity demand due the presence of a heat pump of 60 $\mathrm{kW_{th}}$, integrated with an

[1] Technically, the households in each building must be considered as individual users with their own electricity demand. This aspect is overlooked as the purpose of the case studies is purely illustrative.

heat storage of 100 kWh to supply heating demand of the multi-family residential building. (User 2).

Fig 6 shows the optimised electricity flows in both energy nodes. All values of power are positive definite, but outflows and inflows to the units are plotted as positive and negative, respectively. User 1 injects a large part of the PV overproduction into the grid, since the storage capacity is readily filled. User 2 instead withdraws energy from the grid to fulfill the *instantaneous* electricity demands (load and heat pump), and to charge the battery. Thanks to the presence of storage systems, the user can modify the withdrawals profiles and adapt them to the other user's injections, to exploit the RES generation. Stored electricity is then used locally, but not re-injected into the grid, as it would not account as shared energy.

B. REC with fifty energy nodes

A REC composed of fifty energy nodes of different types (see Table III) has been simulated to prove the scalability of the approach. For sake of simplicity, only the electricity balances on the REC's distribution grid are shown. In Fig. 7, coordinated and individual optimisations of the energy nodes are compared. The two differ on how shared energy is managed: in the coordinate one it is included into the optimisation process by maximizing the REC revenues (9), while in the individual one it is evaluated only after the optimisation of the energy nodes (i.e. cost minimization is adopted in each energy node neglecting the economic benefit of the shared energy).

The energy shared in the REC, calculated according to (9), is highlighted in the figures. In the the coordinated approach, the energy nodes tend to change their injections and withdrawals profiles to let the two quantities match, thus increasing shared electricity. This flexibility is allowed by the presence of storage systems. These, however must be managed to accommodate not only local generation but also energy excess from other nodes to reduce flows to/from outside the REC (ie. exchanges with the National grid), as shown in Fig. 7.

V. CONCLUSIONS

A modelling framework for Renewable Energy Communities named *RECoupled*, tailored on the Italian regulatory framework, has been presented in this paper. REC is modelled as an ensemble of multi-energy nodes connected to the same electricity distribution grid. Nodes can exchange electricity through the grid to increase local consumption of RES generation, reducing the flows with the National grid outside of the REC. A distinction of stored electricity into *local* (i.e. from the same energy node) and *non-local* (i.e. from other nodes) is adopted to properly model country-specific regulatory aspects. However, a similar approach can be adopted in other contexts, for example if it is needed to distinguish between *RES* and *non-RES* stored energy. The scalability of the approach has been tested, simulating both a small REC (only two energy nodes) and a larger one (fifty nodes). Results show that the proposed approach enables a better exploitation of RES generation, since the electricity overproduction can be stored both locally and/or in other nodes of the REC. Consequently, energy nodes should be optimised in a coordinated way to fully exploit such flexibility. In future developments of the work, other technologies and energy vectors (e.g. hydrogen) will be considered, exploiting the modularity of the approach. Moreover, a systematic evaluation of REC and users' KPIs will be implemented to allow optimal sizing of the REC assets.

TABLE III
SET OF DIFFERENT NODES COMPOSING THE REC WITH FIFTY USERS.

N. users	14	10	8	6	6	2	1	1	1	1
PV	✓		✓		✓					✓
BESS	✓			✓		✓		✓		✓
HP					✓	✓	✓	✓	✓	✓
HTS					✓	✓	✓			✓

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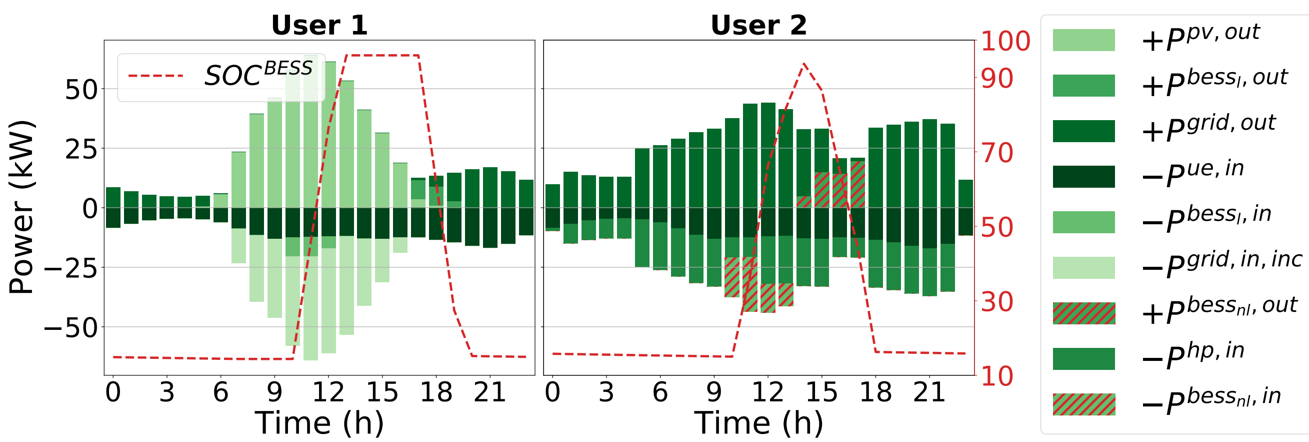

Fig. 6. Electricity balance within single energy nodes in the REC with 2 users.

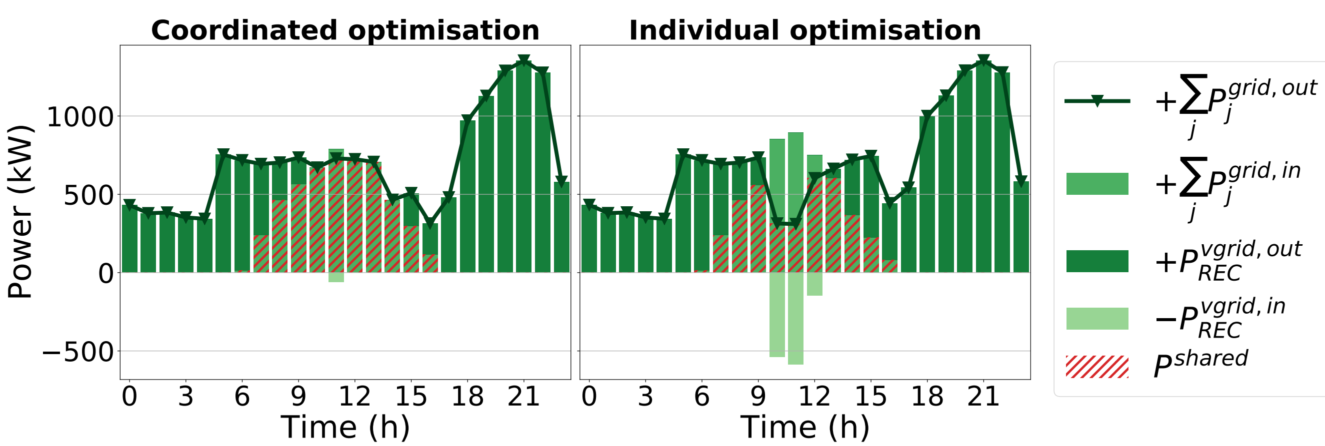

Fig. 7. Electricity balance on the MV distribution grid of the REC with 50 users.