RECOUPLED
A SIMULATION TOOL FOR RENEWABLE ENERGY COMMUNITIES COUPLING ELECTRIC AND THERMAL ENERGIES

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1 SUMMARY

Renewable energy communities (RECs) are legal entities where citizens, small-to-medium enterprises (SMEs) and local authorities join to manage cooperatively energy from renewable sources. Since the regulation requires to evaluate energy fluxes on the hour base, the operative control and performance assessment of these new energy hubs become complex and require the handling of data such as production from renewable energy sources (RES) and end user consumption, that are intrinsically affected by uncertainties. In this contribution, an optimization tool for the operational management of a REC is proposed. RECs can contain renewable energy technologies (photovoltaic or solar thermal panels, biofuel burners), electric, heating and cooling end users and coupling components (e.g., heat pumps). The tool can be used at the planning level to compare different REC configurations based on their performances, assuming optimal management of the available technologies. In this paper, the tool is tested in the simulation of three case studies of collective self-consumption (that in Italy is a REC where all end users are in the same building), located at different latitudes of the Italian country.

Keywords: renewable energy communities; optimization; sectors coupling

2 INTRODUCTION

Italian national law introduced renewable energy communities (RECs) with the decree-law 162/2019, allowing for final customers to join or participate in RECs thus becoming renewable self-consumers. After law has been approved, regulations have been issued to define the operative constraints of the new energy structures and their incentives (Cielo 2021). In this context, an open-source tool had been created to provide quick and easy- to-grasp evaluations of the performances of RECs where electric end users use the public distribution grid to share energy produced "locally" from renewable energy sources (RES) (RECOpt 2021). In the original tool, only electricity was considered, which was produced from a single renewable installation, such as photovoltaic (PV). Then electricity was virtually shared among end users to fulfil their energy demand, instantaneously or through a storage system. The REC model has been recently updated as a multi-node, multi-energy system, which was renamed *RECoupled* (Lazzeroni 2022). In this new version, the REC is assumed to be made by individual nodes, each of them satisfying its energy needs (i.e., electricity and heat) by means of a collection of renewable technologies, storage systems and coupling components (e.g., heat pumps). Electrical energy that is not consumed on site is then injected into the public distribution grid and it can be shared with other members of the community.

A tool to simulate and optimize energy flows in a REC is needed in two different phases. Firstly, at the design stage of the REC, to match the energy needs of the members with a tailored size of renewable generation. Then, the same scheme could be implemented as an "energy brain" of the REC, managing the installations (e.g., energy exchanged with the storage systems), through a proper digital interface, based on the forecasted production and consumption. In this contribution, the tool is used to size three case studies of REC composed of electric and thermal end users located in the same multifamily residential building, where a PV plant is located on the building's roof and integrated with a battery energy storage system (BESS). The aggregated heating demand is supplied by a central unit by means of a heat pump (HP) and a backup boiler, integrated with a "hot" thermal energy storage system (HTS). For planning purposes, the RECs are considered to be located in three different cities in the North, Centre and South of Italy: Turin, Rome and Palermo, respectively. In synthesis, the procedure applied to three test cases highlighted that the optimal PV size is not influenced by the geographical position, while the optimal size of the heat pump increases moving from South to North, as the heating demand is higher. In addition, results show that the presence of thermal energy storage can improve the efficiency of the system.

3 RECOUPLED PROCEDURE

In *RECoupled*, the REC is modelled as a system where RES, both electrical and thermal, are exploited by means of facilities located at "energy nodes". These nodes both inject into and withdraw electricity from the grid. In this way, they can exchange electric power, either among themselves or with the electrical grid outside of the REC boundaries. However, the aim of the REC is to consume locally the energy produced, which is the sum of the "physical" self-consumption (i.e., energy consumed on-site, behind the point of connection with the grid) and of the energy shared between the nodes ("virtual" self-consumption) that is defined as follows:

$$E_{sh}(t_h) = \min\left(\sum_{j=1}^{N} P_{GRID,in}^{(j)}(t_h)\Delta t, \sum_{j=1}^{N} P_{GRID,out}^{(j)}(t_h)\Delta t\right), \qquad \text{(eq.1)}$$

where N is the number of energy nodes belonging to the REC, t_h is the h-th hour interval in the simulation horizon, $P_{GRID,in}^{(j)}(t_h)\Delta t$ is the energy injected by node j during hour h and $P_{GRID,out}^{(j)}(t_h)\Delta t$ is the energy withdrawn by node j in the same interval.

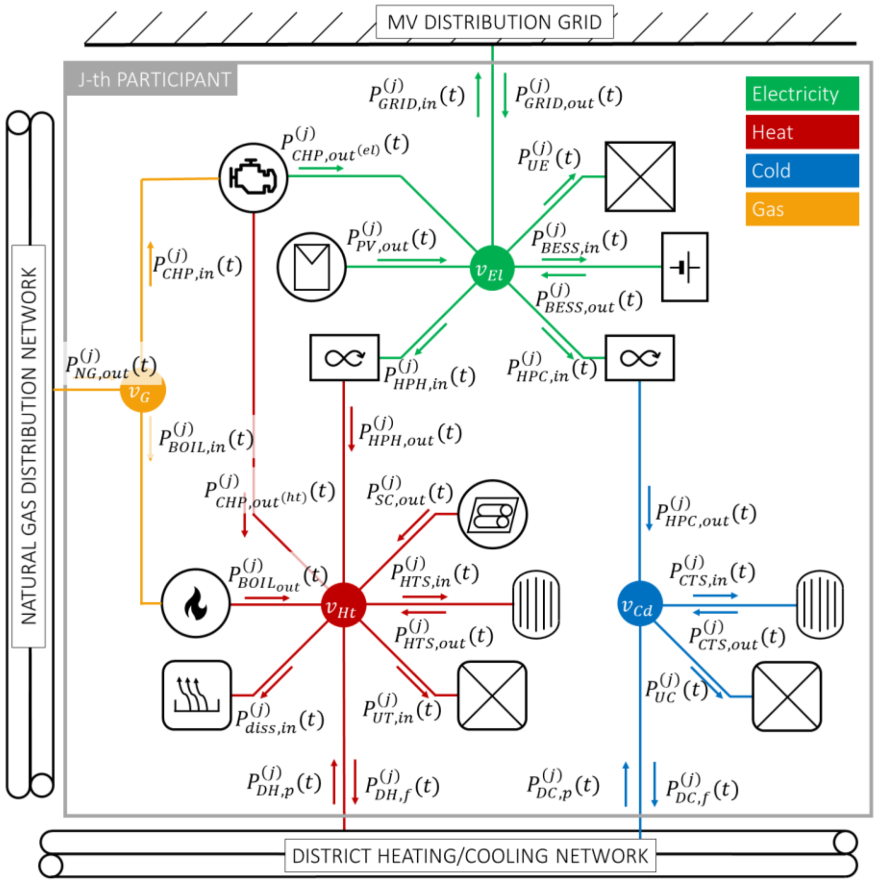
The general structure of each single node in the REC is shown in Fig. 1. The REC's topology in terms of nodes and units (production, conversion, storage systems and loads) is specified in a configuration file. Other data about the specific REC are the year-long hourly timeseries of the RES production and end users' consumption, that the tool reads from csv files. The tool then uses these input data to work out the best scheduling for storage and other dispatchable units to minimize the REC's primary energy consumption. The energy shared among the energy nodes of eq. 1 reduces the need for electricity from the national grid (Canova 2022), thus reducing the primary energy consumption. The *RECoupled* procedure explores the design space of the REC by parametrically changing the sizes of the active components. For each configuration (i.e., a combination of different sizes of the components) optimization of the hourly energy flows within and among nodes is performed by a Mixed Integer Linear Programming (MILP) formulation, considering a limited number of typical days to reduce the computational costs. Typical days are evaluated from the input timeseries through clustering techniques aimed at reducing the loss of information about the original profiles shape (Fazlollahi 2014). Then, based on the optimized energy flows, the procedure extrapolates yearly data (such as shared energy, self-consumption, CO_2 emissions, cashflows, etc.) which are needed to perform the environmental and economic assessment of the different configurations. Finally, all configurations are compared by means of Key Performance Indicators (KPIs) that are evaluated from the yearly values. Examples of KPIs are the electricity self-consumption, the CO_2 emission reduction, and the profitability of the investment for the constitution of the REC.

3.1 Optimization problem

The optimization problem is applied to the proposed model of REC, where each participant is represented by an energy node such as the one shown in Fig. 1. For all these nodes, energy balance equations for each energy vector ensure that the end users' demand is met at all time steps, by properly dispatching the production, conversion and storage units and the energy exchanges with the grid. The energy balance equations take the following general form:

$$\left(\sum_i P_{i,in}^{(v)}(t_h)\,\Delta t + \sum_k P_{k,out}^{(v)}(t_h)\,\Delta t\right) = 0, \qquad \forall t_h, \tag{eq.2}$$

where: $P_{i,in}^{(v)}(t_h)\,\Delta t$ and $P_{k,out}^{(v)}(t_h)\,\Delta t$ are, respectively, the quantities of energy that flow into unit i and out of unit k (production, consumption, storage, conversion units and the grid) and take part to the energy balance of the energy vector v (where v is electricity, heat or cold).



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
GN	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. 1: Node belonging to the REC with electrical, heat and cooling loads. From (Lazzeroni 2022).

Constitutive equations of the units are added as constraint to the problem. Since a MILP formulation is adopted, linear equations are used to model the units' behavior. For conversion units, such as heat pumps, the constitutive equation links the input to the output power (for a heat pump, electricity and heat/cold, respectively) as follows:

$$P_{in}(t_h) = \frac{1}{f_{conv}} \cdot P_{out}(t_h), \qquad \forall t_h, \qquad \text{(eq.3)}$$

where: f_{conv} is a constant conversion factor. which is equal to the yearly average COP for heat pumps.
For production units, such as conventional boilers, the same expression as in eq.3 can be used. The input is the fuel flow measured in power units (primary energy) while the output is heat. In the case of a boiler, the f_{conv} is a constant combustion efficiency.
For storage units, the constitutive equation defines the relationship between input and output powers and the stored energy, as follows:

$$\left(\eta_{in} \cdot P_{in}(t_h) - \frac{1}{\eta_{out}} \cdot P_{out}(t_h)\right)\Delta t + \eta_{sd} \cdot E_{stor}(t_h) = E_{stor}(t_h + \Delta t), \qquad \forall t_h, \qquad \text{(eq.4)}$$

where: $\eta_{in}, \eta_{out}, \eta_{sd}$ are, respectively, the charge, discharge and self-discharge efficiencies, which are assumed constant; E_{stor} is the energy stored in the unit at each time step.
The public grid can be modelled as a slack unit with "infinite" capacity.Output power from RES production units, such as photovoltaic (PV), are not to be optimized since they are not dispatchable. Their output power in all time steps is set equal to the production profile provided as input to the tool. The same applies to the power consumption of loads with assigned demand profiles, such as electricity, heating and cooling demands of the end users. Other equations implement operative constraints such as maximum, and in some cases minimum, input/output power flows or storable energy. Logic variables are used to impose mutual exclusivity between variables that cannot be non-zero at the same time. This is due to physical constraints, for instance on the simultaneous charge and discharge phases of electrochemical storages, as well as the injections and withdrawals into/from the grid. In general, mutual exclusivity constraints are written as follows (Lazzeroni 2019):

$$\delta_i(t_h) + \delta_j(t_h) \leq 1, \qquad \forall t_h, \qquad \text{(eq.5)}$$

where: δ_i, δ_j are binary variables related to the "state" (on-1, off-0) of mutually exclusive quantities.
The previous equations are written for each energy node in the REC, depending on which units are present. One more energy conservation equation is added for the whole REC, linking all participants to each other, as follows:

$$\sum_{j=1}^{N} P_{GRID,in}^{(j)}(t_h)\Delta t + P_{VGRID,out}^{(REC)}(t_h)\Delta t = \sum_{j=1}^{N} P_{GRID,out}^{(j)}(t_h)\Delta t + P_{VGRID,in}^{(REC)}(t_h)\Delta t, \qquad \forall t_h, \qquad \text{(eq.6)}$$

where: $P_{GRID,in}^{(j)}\,\Delta t$, $P_{GRID,out}^{(j)}\,\Delta t$ are the quantities of energy actually injected and withdrawn into/from the public grid by the j-th participant; $P_{VGRID,in}^{(REC)}\,\Delta t$, $P_{VGRID,out}^{(REC)}\,\Delta t$ are the quantities of energy powers virtually exchanged by the REC with the grid, respectively, fed into and taken out from.
Despite the need of maximizing it, the objective function is not set directly as the shared energy since different energy vectors are included. Therefore, the primary energy consumption is taken as objective function. Primary

energy consumption of electricity consumed from the public grid is evaluated dividing it by the average efficiency of the Italian grid, which can be assumed equal to 0.4 (ISPRA 2021). Since the sharing of energy is fully comparable to a physical self-consumption, only the electricity virtually consumed ($P_{VGRID,out}^{(REC)}\,\Delta t$) from the grid takes part in the calculation.

3.2 Key Performance Indicators

KPIs are used to assess the performances of the REC once it is optimized, generally on a yearly basis. When parametrically searching the design space, they are used to compare different REC configurations. Different configurations of the same REC setup are identified by different sizes of the various units. Three groups of KPIs are considered: energy, environmental and economic.

Since the REC's objective is to consume the renewable energy produced locally, energy performances can be measured in terms of self-consumption (SC) (IEA 2016). Environmental KPIs measure instead the reduction in the REC's primary energy consumption or, alternatively, in CO_2 emissions with respect to a base-case scenario where the REC's energy needs in terms of heat and electricity are fulfilled by fossil fuel systems (i.e., the boiler and the electric grid). Finally, economic performances are measured by the investment's internal rate of return (IRR) by assuming, for the sake of simplicity, that all expenses and revenues remain within the REC.

Different KPIs can usually conflict with each other and cannot be maximized at the same time. The REC's sizing hence becomes a multi-objective problem (Minuto 2020). One possible solution is evaluating an equivalent KPI by performing a weighted average of the energy, environmental and economic ones (Hwang 1993). This method has been adopted in the following case studies, where the optimal REC configuration, among those simulated, is the one maximizing the KPI aggregating the SC, CO_2 emissions reduction and the Internal rate of return (IRR). The IRR, defined as the discount rate that zeroes the net present value of the project, is used taking into account the investment for the hardware needed (PV panels, heat pump, etc.) and considering the cash flows coming from the energy community (incentives, selling of electrical energy to the grid etc.). This KPI can give very high values for small investments which, in turn, give very little advantage in terms of energy self-sufficiency or emissions reduction. This fact highlights how the problem is multi-objective with contrasting criteria. Anyway, since the three KPIs are dimensionally consistent (they are all expressed in percentage), a scalar equivalent KPI is evaluated as follows:

$$KPI = w_{SC} \cdot KPI_{SC} + w_{\Delta CO_2} \cdot KPI_{\Delta CO_2} + w_{IRR} \cdot KPI_{IRR}, \qquad with \sum_i w_i = 1, \qquad i = SC, \Delta CO_2, IRR. \tag{eq.7}$$

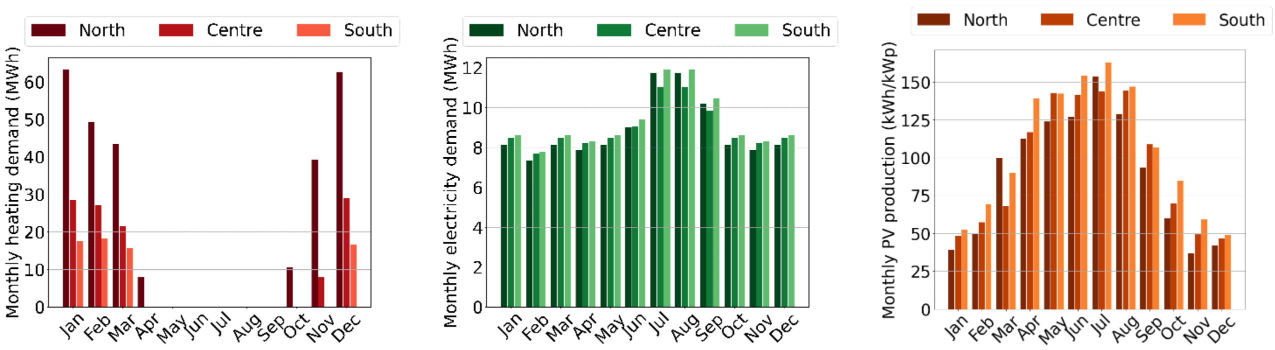
In the following analysis, the three KPIs have been assigned the same weight (1/3). However, since they typically span across different ranges (e.g., SC is typically in the range 50-100 %, while IRR usually reaches smaller values), the plain average of the three KPIs introduces a bias, since it indirectly assigns them different weights.

4 CASE STUDIES

The *RECoupled* procedure has been adopted to size a REC composed of a photovoltaic plant (PV), a heat pump (HP), and thermal/electric storage systems (HTS, BESS) for supplying the heat and the electricity demand of a multifamily residential building. In such cases, the REC is formally referred to as a group of collective self-consumers, to which all household end users are willing to participate as members. Consequently, the REC will partly supply its electricity demand with RES-based distributed generation, which will also cover part of the heating demand, thanks to replacement of the existing centralized heating system (i.e., natural gas boiler) with one based on electricity (i.e., heat pump). Different locations of the residential building have been considered to exploit the *RECoupled* approach at different latitudes, namely North, Centre and South, of the Italian context in Turin, Rome and Palermo, respectively.

The hourly heating/electricity demand, PV production and air temperature profiles were identified to simulate the different REC configurations at different locations. The heating demand was estimated through a simplified approach based on the EN 12831-1:2017 standard, considering the hourly variation of the air temperature extracted by the JRC database (JRC 2021). A representative residential building of 40 apartments and, consequently, its physical characteristics (e.g., heat transfer coefficient of opaque and transparent surfaces) were selected according to the current Italian building stock (Corrado 2014, ISTAT 2021). Then, the heating demand was also corrected according to the Italian framework regulating the daily and seasonal on/off status of the heating systems based on degree days and climatic zones (DPR 412/93 1993). Differently, the electricity demand of each apartment was defined based on a statistical analysis of database (Sibilio 2014), while PV production was extracted from PVGIS database (PVGIS 2021) according to the different location of the case studies.

The k-means clustering technique was finally adopted to identify representative daily loads patterns and daily PV production patterns to reduce the computational cost of the *RECoupled* procedure. Fig. 2 shows the monthly energy demand and the PV production estimated for the different locations.



(a) (b) (c)

Fig. 2: Monthly energy demand and PV production by location of the multifamily residential building.

According to the estimated hourly load profiles and available solar radiation, different sizes of the REC components (i.e., HP, PV, BESS and HTS) have been considered (see Table 1) considering potential limitations such as the available roof surface.

Table 1. Parametric exploration of components' sizes for the three case studies.

Unit	Size min	Size max	Step	
PV	30	70	20	(kW_p)

HP	0 (a), (b), (c)	180 (a), 120 (b), (c)	30 (a), 20 (b), (c)	(kW_{th})
BESS	0	120	40	(kWh_{el})
HTS	0	150	50	(kWh_{th})
(a) North; (b) Centre; (c) South				

Economic and environmental KPIs have been evaluated according to the specific REC configuration and size of the components. CO_2 emissions reductions have been calculated using emission factors (EF) of Table 2. Clearly, some of the assets have no direct CO2 emissions such as PV and BESS. In these cases,CO2 emissions per unit of installed capacity have been considered from a LCA perspective to include indirect impact of those systems in the environmental analysis. Instead, direct CO_2 emissions from grid and boilers have been considered which depend on the energy mix for producing electricity and the fuel to produce heat, respectively.
IRR has been evaluated assuming the investment and operational costs of Table 3, considering the natural gas and electricity price of Table 4 to estimate the yearly cash flows.

Table 2. Emission factors of REC components, in $kgCO_2/kWh$ (ISPRA 2021, Cielo 2021).

Grid	Boiler	PV	BESS (*)
0.2686	0.224	0.050	175
(*) Related to the BESS capacity			

Table 3. Investment and operational costs of REC components (Cielo 2021).

Unit	CAPEX	OPEX
PV	810 €/kW_p	12.5 €/kW_p/year
HP	700 €/kW_{th}	28 €/kW_{th}/year
BESS	350 €/kWh_{el}	8.75 €/kWh_{el}/year
HTS	20 €/kWh_{th}	-

Table 4. Energy price (2019) assumed for the economic evaluation (ARERA 2021).

Natural Gas (€/m^3)	Electricity (€/kWh)
0.90	0.20

Additionally, two incentive schemes introduced by the Italian Government were included: the first one as tax deductions of the investment costs, namely 50% for PV and BESS, 65% for HP and HTS (Decree-Law 83 2012); the second one as economic valorization of both the shared electricity within the REC, i.e. 0.119 €/kWh (GSE 2021) and the electricity injected into the grid (i.e. around 0.05 €/kWh). VAT at 22% and other taxes for a total of 27.9% were applied to the incomes for electricity sold to the grid (Cielo 2021), while the total revenues were reduced by a 10% to include REC's management costs. Concerning the BESS and HP, an operative life of 10 years is considered so that a second purchase is needed in the duration of the investment (20 years).

5 RESULTS

Parametric analyses have been conducted for the three case-studies, exploring the different REC's configurations resulting from all possible combinations of the components' sizes in Table 1. After applying the *RECoupled* procedure, KPIs have been evaluated for all configurations in each case-study.

In general, results show that the REC's IRR can reach values slightly lower than 30%. On the other hand, larger SC values can be achieved (i.e., in the range 50-100%). Concerning reduction of CO_2 emissions, both large values can be achieved (more than 50%), but also small ones (around 10%), depending on the technologies deployed and their sizes. In general, larger IRRs can be achieved in South than North, thanks to the larger PV production, while SC shows the opposite trend, for the same reason. Conversely, CO_2 emissions reduction is larger in the North, where higher heating demand can be met by HP improving environmental benefits.

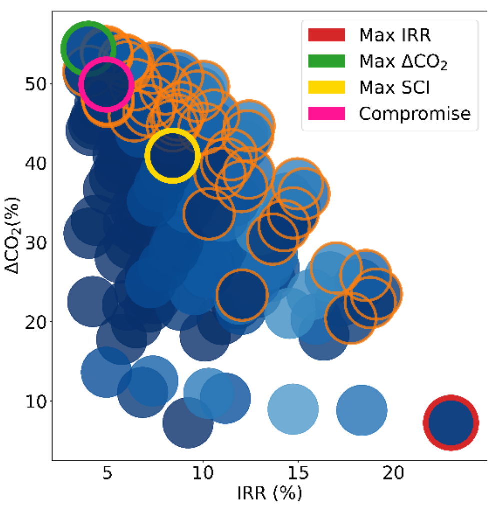
In all case studies, smaller sizes of all the components imply higher IRR with lower CO_2 emissions reduction because of higher duty cycles of REC components. Vice versa, larger sizes correspond to higher reduction in CO_2 emissions, highlighting the conflict between economic and environmental KPIs. Small PV sizes coupled with other larger units lead instead to larger SC.

A "trade-off" table among the three KPIs is presented in Table 5, so that their range of variation can be appreciated.

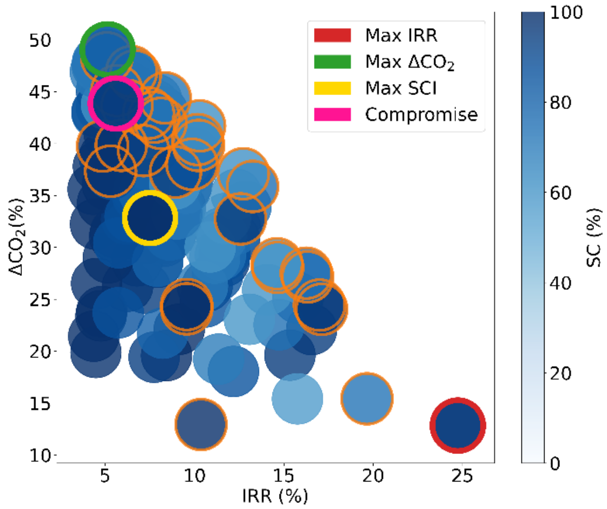
Table 5. "Trade off" table among different KPIs. Configurations A, B and C are the ones maximizing (for each case study) IRR, ΔCO_2 and SC.

Location	configuration	IRR (%)	ΔCO_2 (%)	SCI (%)	PV (KWp)	HP (kWth)	BESS (kWh)	HTS (kWh)
North	A	**23.0**	7.3	95.4	30	0	0	0
	B	4.0	**54.4**	90.1	70	150	120	50
	C	8.4	40.9	**100.0**	30	90	40	150
Centre	A	**24.7**	12.8	95.0	30	0	0	0
	B	5.1	**49.1**	80.1	70	80	80	150
	C	7.5	32.8	**100.0**	30	40	40	150
South	A	**27.5**	17.0	94.4	30	0	0	0
	B	4.8	**51.2**	86.2	70	60	120	150
	C	7.1	35.0	**100.0**	30	40	40	150

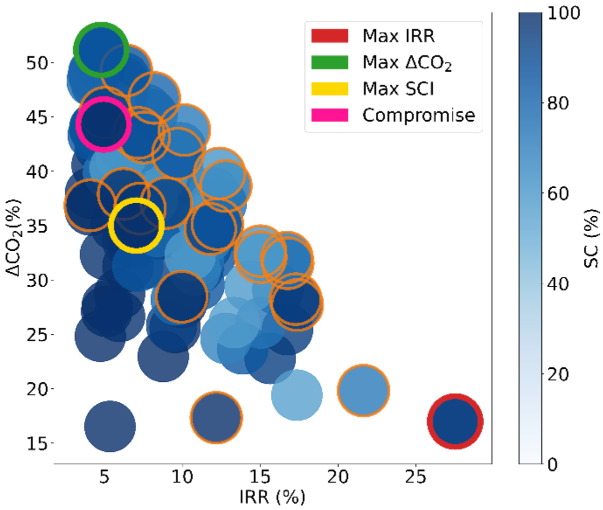
The variation of these KPIs according to the configuration considered is represented in Fig. 3, where the different shades of color provide a measure of the SC. Results confirm that the three KPIs cannot be maximized at the same time and consequently configurations belonging to the Pareto front have been circled in yellow in Fig 3. Nevertheless, a compromise solution maximizing the KPIs can be found if a set of weights for Eq. 8 is properly provided. In this work, KPIs have been equally weighted (i.e., $w_i = 1/3$), assuming that they are equally fundamental for the REC deployment. Of course, different weights distributions could be assumed introducing a certain degree of subjectivity to the problem where, for instance, the economic point of view is perceived as more relevant than others. In Fig. 3, the size of the scattered points gives a qualitative measure of the values assumed by this KPI (i.e., the plain average between IRR, SC and ΔCO_2 emissions), thus providing a full view on the configurations' performances. Moreover, the configurations that maximize the equivalent KPI for each case study are circled in orange and are also summarized in Table 5.



(a) North (Turin)



(b) Centre (Rome)



(c) South (Palermo)

Fig. 3: KPIs in the analyzed configurations for three different case studies.

Table 5. Optimal sizes of REC components for the case studies.

Location	PV (kW_p)	HP (kW_{th})	BESS (kWh_e)	HTS (kWh_{th})	IRR (%)	ΔCO_2 (%)	SCI (%)
North	50	120	120	150	4.9	49.9	99.2
Centre	50	60	80	150	5.6	43.9	94.6
South	50	40	120	150	5.0	44.3	98.7

Optimal PV size is the same in all case studies and smaller than the maximum one, due to the influence of SC and IRR. The optimal size of the heat pump increases moving from South to North, as the heating demand is higher. Interestingly, the HP size is smaller (i.e., 2/3 in the North to 1/3 in the South) than the corresponding maximum one set for the simulation (see Table 1). This is due to the introduction of the thermal storage, which increase the exploitation of HP with lower size compared to the peak of the heating demand: the HTS is charged by the HP production when low thermal demand occurs and discharged when the demand increased, thus increasing the duty cycle of the HP. Both storage systems' sizes are pushed to the corresponding upper bounds set for the simulations, in all case studies. The only exception is the BESS size in North, where the smaller PV production makes large BESS less attractive.

6 CONCLUSION

A simulation tool has been developed to evaluate the economic, energy and environmental benefits of the deployment of renewable energy communities (RECs), where both electric and heating demand are supplied through more efficient and/or renewable energy sources. In this work, the tool has been employed to size the REC units (i.e., heat pump, photovoltaic, electric and thermal storage), while their optimal scheduling is performed to minimize the primary energy consumption. Different case studies in the North, Centre and South of Italy have been considered to exploit the opportunity offered by a particular REC configuration (i.e., collective self-consumption) for a multifamily residential building located at different latitudes.

A parametric mapping of the sizes of different components: photovoltaic, heat pump, battery energy storage and thermal energy storage has been performed and KPIs for each configuration have been computed. The analysis of the results shows that the KPIs are conflicting and that a Pareto Front of non-dominated solutions can be detected among all points. Finally, the equally weighted average sum of three major KPIs: internal rate of return, reduction of CO_2 emission and self-consumption index has been minimized to find a point belonging to the front and balancing among the three KPIs.

These results highlight how energy, economic and environmental points of view are typically in contrast, but compromise solutions can be found reaching an equilibrium of the different aspects. The introduction of storage solutions increases REC sustainability and flexibility by improving RES exploitation. Moreover, the electrification of the heating demand represents a valuable option for decarbonizing the energy consumption of residential building. Finally, thanks to *RECoupled* replicability, analysis of the REC diffusion for planning purpose will be performed in future work through the adoption of the simulation tool at the country level.

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