Virtual energy sharing and energy communities for the Municipality of Milan: the case of the Chiaravalle area

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Abstract. The development of virtual energy sharing in complex realities such as the territory of the Municipality of Milan requires the integration of political and social strategies, technical analyses and the use of more advanced urban modelling techniques. This work aims to describe the strategy developed by the Municipality of Milan for the implementation of energy communities and virtual energy sharing, on the basis of current legislation, with reference to the case study of the Chiaravalle area. In order to carry out studies on the area, UBEM (Urban Energy Modelling) models were developed and various intervention scenarios were analysed. The results of the analysis and the technical and strategic evaluations developed are presented.

1 Introduction

Renewable energy communities (RECs) have been identified as key tools in supporting the transition to sustainable development and renewable energy sources [1]. In 2019, the Clean Energy for All Europeans Legislative Package (CEP) [2] acknowledged the pivotal role of energy community (EC) ownership in advancing the European Union's climate and energy objectives [3], [4]. The CEP introduced a facilitative legislative framework designed to empower citizen and renewable energy communities. Notably, two directives within this package marked a historic milestone at the European level by explicitly recognizing the EC concept [3], [5] . The Directive 2008/2001, a revision of the European Renewable Energy Directive (RED II), provided a comprehensive definition of the Renewable Energy Community (REC) [6]. Simultaneously, the Directive 944/2019, known as the Internal Electricity Market Directive (IEMD) and focused on electricity market design, delineated the model for Citizen Energy Communities (CEC) [3], [7]. In this context, the Italian interpretation of European regulatory packages on RECs provides opportunities for consumers, businesses, and institutions, with available funding potentially strengthening the Italian energy market.

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In Italy, the period between late 2019 and early 2020 witnessed the initiation of a partial and early transposition of the RED II, primarily through the "Milleproroghe" decree-law (converted into the Law n.8, on 28 February 2020) [8]. This transitional framework facilitated the experimentation of RECs configurations, including “jointly acting renewables self-consumers”, introducing specific constraints such as a maximum eligible nominal power of 200 kWp and connection to the same Low/Medium voltage substation [9]. The Italian Regulatory Authority for Energy (ARERA) and the Ministry of Economic Development subsequently defined regulatory models and tariff components for RECs and collective self-consumption schemes, incorporating a virtual regulatory model for managing RECs [10], [11].

In December 2020, the first Italian REC was established under this transitional regulation (Mise, 2020). Throughout 2021, additional RECs were activated, revealing critical elements and limitations. The full transposition of RED II in Italy occurred through Legislative Decree no. 199 in November 2021, enabling the development of large-scale energy communities [12]. Notable innovations included increasing the eligible nominal power to 1 MWp and expanding the community to include users connected to the same Medium/High voltage substation. The Legislative Decree no. 199 came into force on December 15, 2021, triggering deadlines for updating regulations and support mechanisms. ARERA published the "Integrated Regulation for Diffuse Self-Consumption" (TIAD) [13] at the end of December 2022, while discussions on the decree defining financial support mechanisms continued.

Article 14 of Decree 199/2021 established criteria for coordination between the National Recovery and Resilience Plan (PNRR) and sectoral incentive instruments. PNRR's Mission 2 allocated funds to support the installation of 2 GW of RES facilities in REC and self-consumption schemes in small towns [12], [14]. However, the delay in publishing regulatory documents and incentive support mechanisms for RECs in 2022 hindered the deployment of large-scale RECs, affecting PNRR calls to stimulate REC development.

On the 23rd of January 2024, the Ministry of the Environment and Energy Security published the latest decree [15], defining the regulatory framework for the incentives and the rules for the participation to a REC project. Soon, the publicly-owned company promoting and supporting renewable energy sources, the GSE S.p.A, will publish the technical guidelines, ending the legislative process.

A mapping initiative of Renewable Energy Communities (RECs) in Italy, highlighted in the "Orange Book 2022" by Fondazione Utilitatis and Ricerca sul Sistema Energetico , identified about 20 established REC experiences [14]. These predominantly involve photovoltaic (PV) plants with nominal power between 20 to 60 kWp, reflecting the technical and economic feasibility of solar energy technologies in the national and local context.

The activation of RECs in Italy faced delays due to the postponement of regulatory guidelines and incentive decree publication. Despite this, there is notable interest and activity in REC development, supported by national and regional calls, modelling platforms, and informational events. Italy's energy legislation involves collaboration between national and regional authorities, with regions actively promoting REC initiatives. Piedmont and Puglia were early adopters, enacting laws in 2018 and 2019, respectively, to incentivize REC development [1]. Most Italian regions have implemented measures to support RECs, with 16 identified regional initiatives as of September 2022. Supra-regional efforts include initiatives from foundations like "Fondazione Cariplo" and "Fondazione con il SUD," targeting municipalities and non-profit organizations [16], [17]. National funds, such as those from the National Plan for Complementary Investments (PNC), support programs like “NextAppennino”, allocating 68 million euros to create energy communities in seismic areas [18]. The PNRR allocates 2.2 billion euros for REC promotion in municipalities with fewer than 5000 inhabitants through the M2C2 measure [19], [20]. Despite setbacks, these initiatives reflect a growing commitment to foster REC development in Italy.

The development of RECs in Italy involves both public and private initiatives, aiming to exploit renewable energy and provide social, environmental, and economic benefits to community members. Public administrations play a crucial role, acting as major aggregators and promoters of RECs through national and regional calls. Local authorities facilitate projects by providing assets, such as public building rooftops, and creating regulatory and financing frameworks to encourage citizen participation in energy transitions.

Different REC models are being developed, with three main trends identified based on stakeholder involvement and goals: bottom-up, top-down, and energy operator-driven. Studies in 2021 highlighted these models, summarizing their characteristics, including stakeholders, goals, funding, subsidies, and benefit distribution among the members . In Italy, the majority of the initiatives fall under the top-down approach, led by local authorities or non-profit organizations [1]. In this context, small municipalities face challenges in technical and administrative expertise, while large municipalities struggle with citizen engagement and aggregation criteria. The organizational form of a REC with local authorities as members requires careful consideration due to regulatory limitations and the preservation of flexibility within the community. The bottom-up or citizen-driven model involves citizens and small-to-medium enterprises (SMEs) making investment and legal/technical decisions, requiring significant financial and management efforts. Energy operator-driven initiatives involve companies investing in and deploying renewable energy projects, defining business models based on services provided. Coordinating actions by agencies, authorities, or organizations can facilitate REC implementation, tailoring the form to members' needs, territorial characteristics, and business cases. Successful REC development requires collaboration, proper member information, and the creation of a solid, socially and economically productive REC.

2 Municipality of Milan: electricity sharing strategy and vision

The Municipality of Milan has long been committed to the issues of reducing polluting and greenhouse gas emissions through comparison with other institutions and membership of international networks and initiatives, including the C40 Cities Climate network, the Urban Agenda Partnership for Air Quality, the Covenant of Mayors, the Resilient Cities Network and the EIT Climate-KIC initiative. The Administration has signed medium and long-term commitments that integrate regulatory obligations for air quality and the reduction of greenhouse gas emissions; the signed commitments also involve the development of specific planning tools aimed at respecting the stipulated targets.

In this context, with resolution no. 4 of 21 February 2022, the City Council approved the Air and Climate Plan (PAC) (Comune di Milano a), 2022), an urban instrument aimed at reducing air pollution, mitigation of climate change and defining adaptation strategies for the area of the Municipality of Milan , respecting the principles of the right to health, equity and justice, considering the criteria of social inclusion and the protection of the weakest people as priorities; the Air and Climate Plan is a document of a strategic and policy nature, which identifies specific priority areas of intervention, for each of which intermediate objectives for 2025 and 2030 are identified, in line with the challenges and medium-term commitments undertaken by the Municipality. Each objective is then broken down into the actions necessary to implement the Plan. In “Area 3 - Milan with Positive Energy - An urban system that consumes less and better” (zero-emission building stock and a smart urban energy system powered 100% by renewable sources), the following actions are envisaged, among others:

- 3.2.1 Redevelopment plan for the building heritage of the Municipality of Milan;
- 3.2.2 Pilot project for the installation of photovoltaic systems renewable electricity production to cover the consumption of the Municipality
- 3.5.2 Development of agreements for the development of energy communities.

The Municipality of Milan is also a partner of the HORIZON 2020 project, NRG2Peers (NRG2peers, 2023), which has as its aim the support to the development of energy communities in Europe and the increase of awareness among European citizens regarding the benefits of energy sharing. The project also aims to carry out some feasibility studies to support the creation of various energy communities in Europe. The design of a feasibility plan for the energy community of Chiaravalle (Milan) is also envisaged.

The Municipality of Milan has defined its strategy on virtual energy sharing with the publication of City Council Resolution no. 24 of 04/20/2023 "Guidance act for the definition of a program to promote widespread self-consumption of energy from renewable sources and energy communities in the Milan area" (Comune di Milano b), 2023).

This document specifies the approach that the Municipality has chosen, based on the different configurations of virtual energy sharing in compliance with national legislation: individual virtual energy sharing (sharing of electricity within buildings and assets owned by the Municipality of Milan), jointly acting renewables self-consumers, and renewable energy communities.

The Municipality's strategy is based on the following 5 fundamental points:

1. valorisation of surplus energy produced by existing photovoltaic systems or to be built on municipally owned properties through the configuration of remote individual self-consumption, which allows the exploitation of surplus energy for the benefit of the Municipality itself. The aforementioned configuration is not only of less managerial and technical complexity, taking into account the numerous and functional heterogeneity of the properties available to the administration, but above all of direct and immediate advantage for the organization;
2. encouraging the development of renewable energy communities through an agreement for the transfer of surplus electricity produced by their plants only to the communities whose proposals for use the incentives are of a solidarity or social nature (CERS – Social Renewable Energy Community); this solution is to be preferred in the event that the direct participation of the Administration in the CER does not bring added value. The project proposals, financed by the incentives, must also involve well-defined local identity area (called NIL) and contribute to the pursuit of the organisation's targets, excluding direct redistribution to members, without prejudice to that possibly foreseen in a specific project aimed at supporting the members or citizens who are in fragile conditions;
3. active participation through the establishment, in the foreseen associative forms, and/or membership of the Administration in a Renewable Energy Community in the case of proposals for the valorisation of incentives which are of a solidarity or social nature (CERS), this solution is to be preferred in the case of multiplicity of CER members as prosumers. In this case, the prior establishment, in compliance with the current name, of a recognized association will be necessary, including in the form of a social cooperative, a participation foundation or other forms deemed suitable by law. In this case, the economic incentives and revenues linked to the valorisation of the electricity send to grid and shared, provided by GSE S.p.A. must be intended for the creation of services with a predominantly social and environmental value aimed at the community itself, excluding direct redistribution to members, without prejudice to that possibly foreseen in a specific project aimed at supporting members or citizens who are in fragile conditions, as best identified by the decision-making bodies of the ESRB; for projects that concern from the outset a plurality of municipal buildings and provide for a CER with subjects already established in legal forms, the Administration will join as a partner, identifying, based on regulatory developments, the most suitable legal form for the establishment of the CERS. In

such cases the Administration will be able to join both as a prosumer and as a consumer;

4. promotion of the establishment of jointly acting renewables self-consumers, for public residential buildings, in collaboration with the company MM S.p.A.;
5. promotion of Renewable Energy Communities and jointly acting renewables self-consumers in the Milan area through the Energy Desk, with a role of facilitator for SMEs, associations and citizens but without establishment/adhesion to this reality by the Municipality.

On a case-by-case basis, the best configuration will be chosen based on the characteristics of the users, their power load profiles and the economic return on the investment.

The local network operator (UNARETI S.p.A.) has defined 19 areas relating to primary HV-MV substations for the Municipality of Milan. These areas do not directly fit with the 9 districts and the NIL areas. The 19 areas represent the reference areas for the development of potential RECs (Figure 1).

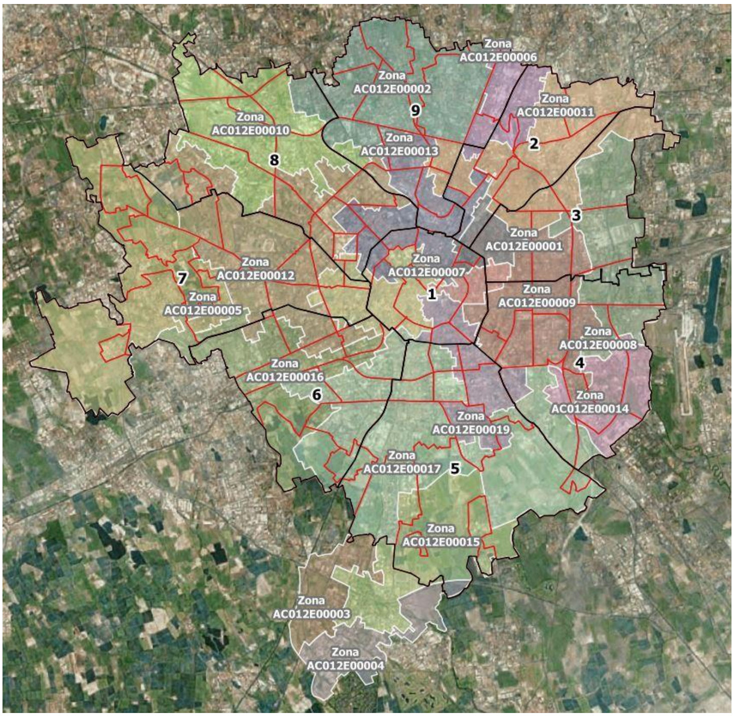

Fig. 1. 19 areas relating to primary HV-MV substations (numbered AC…..), municipality district (black lines numbered from1 to 9) and NIL (red lines).

The first step of CERS development includes five test cases, described in the same City Council Resolution, that involves different areas of the city:

1. the first CERS will be born from the initiative of an association promoted by a group of parents, school teachers and citizens of the Ghisolfa district, and its development will be based on photovoltaic systems built on the roofs of the schools themselves;
2. the second and third CERS will be developed thanks to the initiative of the Polytechnic of Milan in two different areas, Città Studi and Bovisa; the

photovoltaic systems involved will mainly be installed on the roofs of university buildings and some municipal buildings;
3. the fourth CERS will be developed in collaboration with Cooperativa Abitare, a cooperative of inhabitants, and will be developed in the Niguarda area; the project proposal involves the promotion of initiatives to support the territory in which the Energy Community operates, for example support for vulnerable users such as the elderly and disabled, support for energy poverty;
4. the fifth CERS, promoted by a cultural association, is instead located mainly in the Borgo di Chiaravalle, although it involves some systems on some public buildings belonging to the same primary substation located in other neighbourhoods; it will be a Renewable Energy Community of a supportive nature, thanks to the available incentives, it will be possible to create opportunities for cultural, youth and social aggregation for the residents of the area, as well as develop the potential of Chiaravalle as a cultural centre of the area, also in line with the history of the village, enhance the economic development opportunities linked to the use of renewable energy, so that new businesses and new local activities can be developed; finally facilitate local development opportunities and its attractiveness while maintaining the peculiar characteristics that make Chiaravalle a village located in a peri-urban context with still an agricultural vocation.

Chiaravalle area is the subject of the modelling described in the following paragraphs and the characteristics of the photovoltaic systems involved will be better described in the following sections.

3 Development of the optimisation tool

The design of a REC presents multifaceted challenges, particularly in urban areas characterised by high population density and limited space for renewables. In this context, the effectiveness of decision-making is paramount, yet hindered by the absence of a reference design framework and evaluation criteria. In Italy, local authorities (LAs) assume a pivotal role in the implementation of REC models, especially in the initiation phase, before the actual design. During this project stage, LAs focus on evaluating the feasibility of REC model implementation in their respective territories. However, the project increases in complexity as LAs simultaneously pursue environmental, economic, and performance objectives. To address this challenge, there is a pressing need for the development of a supporting tool to facilitate LAs during the initial design stages of a REC project in urban contexts. Such a tool would address the assessment of feasibility and optimise decision-making processes. To this aim, we present a tool designed to provide LAs with a quantitative approach addressing multiple and conflicting objectives. The tool utilizes the synergy between multi-objective optimisation (MOO) models and multi-criteria decision-making (MCDM) methods. The MOO model identifies a diverse set of efficient solutions, while MCDM evaluates and compares these solutions based on stakeholder preferences. By integrating MOO and MCDM, the tool empowers LAs to explore various REC design solutions simultaneously facilitating informed decision-making aligned with their priorities.

The tool consists of three stages (Figure 2):

1. District modelling and simulation: a full analysis of an existing urban district using bottom-up physics-based Urban Building Energy Modelling (UBEM) tools; this stage simulate multiple REC scenarios and compare the potential REC configurations. It concurrently evaluates energy use, generation, environmental impact, and economic factors;

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2. Optimisation: this stage addresses the aggregation problem of REC members in a district under multiple technical configurations. Exploiting a famous Linear Programming (LP) model as the baseline. The model is integrated to represent the whole combinatorial problem. The final mathematical optimisation model is run through a Python-based algorithm;
3. Decision-making stage: MOO results are exported to assess the optimum solution among the set of Pareto solutions. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is employed, combining multiple solutions and key parameters from the optimisation process with weighting criteria identified by stakeholders.

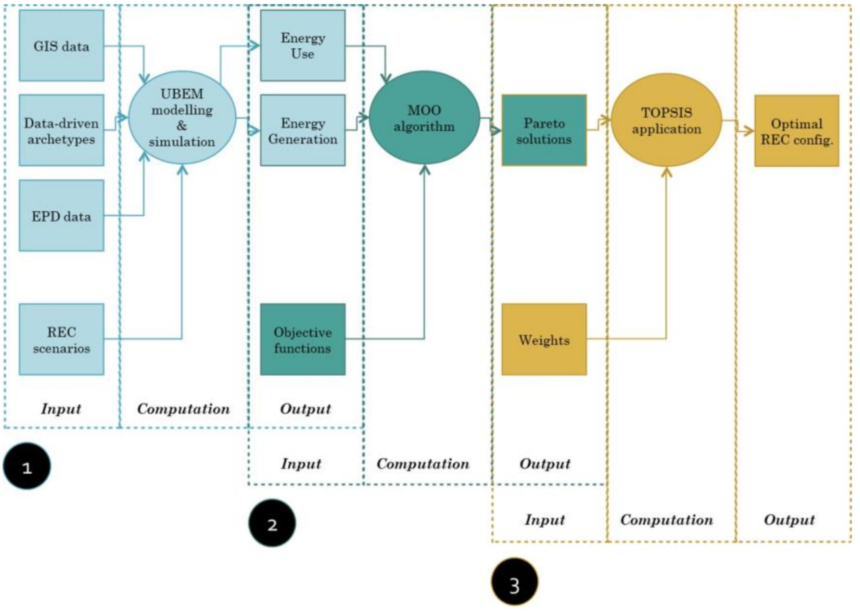

Fig. 2. Flow chart describing the different stages of the tool.

3.1 District modelling and simulation

The district's environmental features and geometries, derived from weather and GIS databases, are modelled using Rhinoceros® (McNeel & Associates, 2023). The simulation unfolds in two steps: (i) employing a UBEM tool to simulate the REC embodied greenhouse gas (GHG) emissions and energy use based on data-driven building archetypes, (ii) conducting the simulation of on-site energy production from Renewable Energy Sources (RES). Both analyses leverage the same computational tool: the *urban modeling interface* (umi), developed by MIT (MIT, 2023). Key inputs involve a comprehensive district characterization, building use profiles, thermophysical and systems characterization, materials' environmental impact, and RES systems. This characterization is encapsulated in "building archetypes", prototypes representative of entire building typologies based on factors such as (i) use destination, (ii) year of construction, and (iii) geographic location. These archetypes address issues related to data scarcity, normative reference data obsolescence, and the challenges of time-consuming monitoring campaigns [21], [22], [23].

3.2 Optimisation

The MOO model is designed to combine environmental, economic, and technical performance aspects, aiming to highlight the optimal configuration for a REC within a specific district. The idea is to compare and quantify the differences between multiple REC configurations. In this sense, the configuration of the REC varies according to different potential final users (aggregation problem), diverse PV equipment (on-site energy generation curves), and different scenarios of energy retrofit and electrification of uses (district energy use curves).

The methodology for our computational tool focuses on solving a modified Set Partitioning Problem (SPP) within the context of a Multi-Objective Optimization (MOO) framework [24]. The optimization model is designed as a Mixed-Integer Linear Programming (MILP) to address the complexity of the REC implementation in city districts. The tool aims to identify the optimal combination of users, considering multiple scenarios of energy retrofit and electrification, with three distinct objective functions: economic, sustainability, and technical performance.

The code defines a mathematical optimization model using the Pyomo library to solve the SPP [25]. The SPP is a combinatorial optimization problem where you aim to partition a set of elements into subsets (combinations) in such a way that each element belongs to exactly one subset, and a certain objective function is optimized. Specifically, in our problem multiple conflicting objectives need to be considered, therefore the problem was re-designed as a MILP.

3.3 Decision making stage

The result of the MCDM analysis is conceived to reflect the stakeholders' priorities. At the stage of MCDM, the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method was selected. The relative closeness degree of all Pareto solution sets with ideal and non-ideal solutions are calculated. Through this method it is possible to sort the solution sets and evaluate their relative merits, achieving the identification of the optimal solution. TOPSIS includes standardization, calculation score and normalization (Figure 3).

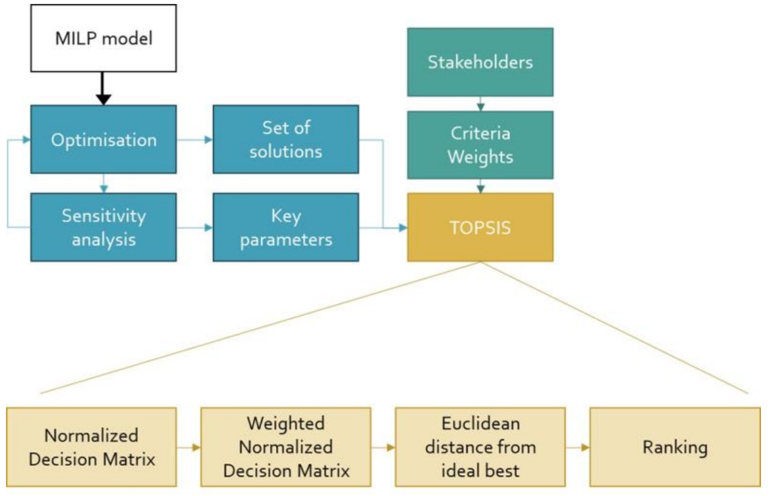

Fig. 3. Decision making process.

3.4 MILP optimisation algorithm

The optimization methodology employs a systematic approach to derive optimal solutions. The problem is cast as a SPP, where decision variables indicate the inclusion or exclusion of users from each community. The three objective functions are evaluated separately, leading to a set of solutions. Exploiting the capabilities of the Gurobi solver, our tool tackles the MILP formulation. This integration produces optimal solutions for user assignments and associated energy retrofit/electrification scenarios. The objective functions and constraints are linear functions of binary variables, making it a linear programming problem [24]. MILP is a widely used approach for solving various combinatorial optimization problems where the decision variables are integers or have discrete values [26], [27], [28]. In particular, the optimization framework encompasses three distinct linear objective functions, tailored to address the key aspects of a top-down REC model:

- Economic Objective: This function assesses the financial feasibility and cost-effectiveness of REC formation. It considers variables such as investment costs, maintenance of the equipment, and potential revenue streams derived from energy production and savings;
- Sustainability Purpose: Quantifying the environmental impact and sustainability of each REC, this objective integrates metrics related to carbon emissions reduction, energy efficiency improvements, and the overall ecological footprint of the communities;
- Technical Performance: Evaluating the technical efficiency of each REC, this objective considers parameters such as the configuration of energy sources, and the energy matching between energy use and generation of each community.

Constraints are formulated to ensure set partitioning and coverage of all users. While the decision variables are designed to represent the configuration of multiple REC models in a city district:

- Assignment Variables: binary indicators defining the assignment of users to specific REC groups. These variables dictate the composition of each community by specifying the grouping of users;
- Scenario Variables: continuous variables representing the energy retrofit or electrification level for each user or building.

The tool explores a diverse array of energy retrofit and electrification scenarios. This exploration allows for a deeper understanding of how optimal solutions respond to various technological and policy interventions. By this methodology, our computational tool not only identifies optimal user combinations for REC formation but also provides valuable insights into the various trade-offs and synergies among economic, sustainability, and technical performance objectives under different energy retrofit and electrification scenarios.

The optimisation stage begins by defining key parameters crucial for optimizing the formation of REC models. Parameters include the number of users, the percentage of photovoltaic usage, the percentage of electrification of final uses, and various economic and technical factors. The required inputs are the energy generation, use, and kWp information for each user, at an hourly resolution. Data can be derived from energy simulations (i.e., exploiting UBEM tools) or they can be real data (i.e., from monitoring campaigns). To explore the diverse user combinations within the communities, the script utilizes the *itertools.combinations* function. Combinations are generated based on a given specified minimum size of each REC, and the results are stored for subsequent analysis. The script computes the emission calculations, operational costs, self-consumption, and incentives for each combination. To formalize the optimization problem, a Pyomo model is constructed.

The model is solved using the Gurobi solver, chosen for its efficacy in handling MILP problems. The combination of Python scripting, Pyomo modelling, and Gurobi solving ensures efficiency, scalability, and adaptability for diverse REC scenarios, making it a valuable asset for public administrations and local authorities in implementing REC models.

3.5 Case study

To validate the efficacy of our optimization tool in real-world scenarios, we selected a case study in collaboration with the Municipality of Milan. This case study aimed to apply our computational framework to a specific urban district, demonstrating its practical utility in optimizing the formation of RECs.

The early analysis conducted on the reference case study allowed the identification of the relationships among the key parameters. The case study is a residential neighbourhood, Chiaravalle, located in the southern area of Milan, Italy (Figure 4). This neighbourhood, selected by the Municipality of Milan as a pilot REC project within the European initiative NRG2peers (NRG2peers, 2023), consists of approximately 49 buildings and 1400 inhabitants. The case study's modelling took place in a 3D virtual environment using the Rhinoceros® CAD backbone. This step involved the characterization of each building's envelope, systems, and operation schedules, leveraging archetypes developed in umi.

Fig. 4. Decision making process.

We gathered comprehensive data pertaining to the urban district, including energy generation patterns, use profiles, and existing infrastructure. This data, derived from open-source databases, was meticulously prepared and aligned to ensure compatibility with our computational tool.

The two main key parameters evaluated at this stage are the REC self-consumption (E_{sc}) and shared energy (E_{sh}). The E_{sc} parameter is calculated on an annual basis. It provides information about the overall performance on a REC, in terms of exploitation of PV systems to fulfil the electric energy use [22].

$$E_{sc} = E_{D}^{yearly} - E_{D,Net}^{yearly} = \sum_{i=1}^{n}\sum_{t=1}^{8760} E_{D}(i,t) - \sum_{i=1}^{n}\sum_{t=1}^{8760} E_{D,Net}(i,t) \quad (1)$$

Where:

- E_{D} = Energy use (i-th building, t-th time interval)
- $E_{D,Net}$ = Net energy use (i-th building, t-th time interval)
- E_{G} = Energy generation (i-th building, t-th time interval)

The E_{sh} indicator is evaluated on an hourly basis. It is associated with economic incentives, and it helps understanding the performance of the energy sharing at the district level.

$$E_{sh} = \sum_{i=1}^{n} \sum_{t=1}^{8760} min[E_D(i,t) \; ; \; E_G(i,t)] \quad (2)$$

Where:
- E_G = Energy generation (i-th building, t-th time interval)

In this phase, the primary outcomes involved identifying key parameters and energy use and generation profiles for the entire district across various REC configuration scenarios. These outcomes served as the foundation for constructing the optimisation model. Adapting our optimization tool to the unique characteristics of the urban district, we fine-tuned parameters, such as the number of users, photovoltaic usage percentages, and electrification levels. This customization aimed to enhance the tool's applicability to diverse urban contexts. Also, the definition of the objective functions was crucial, and it is still refining. The functions are representative of the three scopes. These functions are conflicting, and the goal of the optimisation is to find a set of solutions on the Pareto front. Figure 5 represent the essential parameters on which the objective functions were based. Each curve represents hourly data, evaluated on a yearly basis.

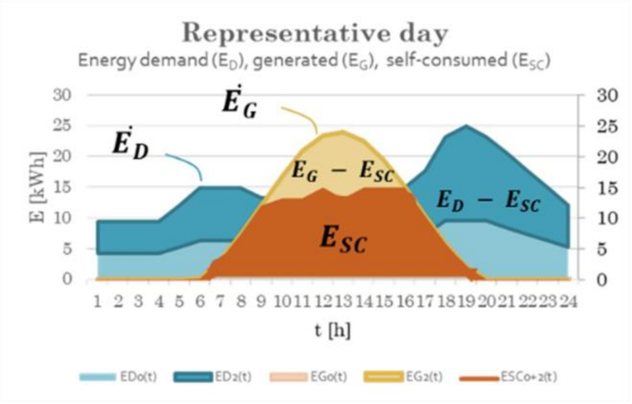

Fig. 5. Representative day – hourly energy parameters.

Fundamentally, the environmental objective aims to minimize the hourly difference between the energy uses and the self-consumption (E_D (t) – E_{sc} (t)) for the entire district; the economic objective minimizes the yearly costs referred to the entire district which is designed as function of the energy uses, the energy generation, and the self-consumption (E_D (t), E_G (t), E_{sc} (t)); and the performance objective which aims to minimize the difference between the energy generation and the self-consumption (E_G (t) – E_{sc} (t)).

The first application ended with a sensitivity analysis, revealing the implication of the REC modelling on the combinations evaluated through the MOO model. This kind of analysis provides insights into how the model's outcomes might change in response to variations in key parameters or constraints. Sensitivity analysis is paramount in assessing the robustness and reliability of optimized solutions obtained from our computational tool. By varying key parameters and evaluating their impact on solution outcomes, we gain insights into the stability and adaptability of the REC configurations under different conditions. The parameters variation was structured into four sections:

- Energy Retrofit Scenarios: different levels of energy retrofit, ranging from minimal (normative compliance) to extensive retrofit measures, are considered;

- Photovoltaic system: different scenarios of PV system extension, from 15% of available roof area to 100%;
- Electrification Levels: varying degrees of electrification, from zero to complete electrification of energy uses, are explored;
- Neighbourhood extension: sensitivity to changes in the number of buildings, from a minimum of 5 to 20.

The analysis is conducted as a one-at-a-time analysis, for which parameters are varied individually while keeping others constant to observe their isolated effects on the optimized solutions [29]. This method helped to identify the most influential parameters, leading to important conclusions on the way the model behaves according to the modelling of REC configurations. As main outcome, the analysis revealed that the parameters affecting the most the model are (i) the number of buildings, (ii) the amount of PV systems, (iii) the emission factor, and (iv) the energy cost. Also, it showed that the higher the number of buildings, the higher the sensitivity of the model to the amount of PV systems, and the higher the number of buildings, the less the sensitivity to the emission factor. These conclusions were adopted to refine the model for future analyses and applications to additional case studies.

Specifically, the case study was investigated considering the specific features of the context (i.e., the social and economic framework, the geographic location), the hypothesis of the triggering role of a public administration, and the normative in force at the moment of the study. For this reason, an organic vision of the district is kept as baseline for all the scenarios, i.e., electrification of uses and energy retrofit interventions are modelled as percentages of the neighborhood, as consequences of eventual collective actions. The scenarios evaluated derived from these considerations and are reported in detail in the work of Ferroni et al. [22], where early quantitative results are showed and discussed.

The case study offered valuable lessons in the application of our optimization tool to real-world contexts. Future directions include further refinement of the tool based on additional case studies, expanding its applicability to different urban set-tings, and incorporating evolving technological and policy landscapes.

4 Energy sharing in Chiaravalle

The analyses conducted by the Polytechnic of Milan, thanks to the support of the European project NRG2peers [30], were the basis for the development of the preliminary analysis of the CERS in the Chiaravalle area, one of the five pilot projects being developed by the Municipality of Milan, described in the paragraph 2.

From the point of view of virtual energy sharing, the Municipality is actually carrying out two different projects in the area:

- a high-power photovoltaic system (around 600 kW) is in the design phase and will be built in the future on the roofs of the Chiaravalle cemetery; this system will be intended for widespread individual self-consumption, with sharing of the electricity produced in other municipally owned buildings;
- the systems on existing ERP (social housing) buildings will be expanded and additional systems will be created on other buildings owned by the Municipality, to make them available to the CERS.

The first members of the CERS will be:

- a cultural association;
- the Municipality of Milan, which will make the electricity produced by its plants available;
- organizations involved in social care for minors and the elderly, which use two public buildings;

- private citizens;
- public residential buildings.

Overall electricity consumption is approximately 337 MWh, of which approximately 30% in the F1 range (daytime on weekdays).

The photovoltaic systems that are planned to be built will be realized on the roofs of public buildings and condominiums for a total power of 330 kWp and an annual electricity production of 355 MWh/year. Part of this electricity will be self-consumed by the buildings (37%), but the remaining 63% (equal to approximately 224 MWh) will be available for virtual sharing by the CERS.

The amount of electricity send to grid, is relatively simple to share, as the affected area is very large and involves an huge amount of buildings and citizens. However, in the subsequent development phases of the project, the concrete challenge will consist in the involvement of the people in particular who occupy the public residential buildings. The social context is very complex and specific stake-holder engagement techniques must be developed to obtain the desired results.

This first nucleus, is the basis for developing further photovoltaic systems and involving further consumer or prosumer users, in order to reach the potential envisaged by the simulation models developed.

5 Conclusions

The case study presented highlighted how the development of energy communities can also make use of more advanced analysis tools. The process developed by the Municipality of Milan is leading to favouring the development of energy communities with investment of the revenues obtainable from incentives with pre-dominantly social purposes or intended for the local community, without distributing to each participant a portion that would be of low economic value and would not stimulate individual participation. The use of economic benefits for collective purposes also has the advantage of simplifying the economic and fiscal management of the CERS, which in the public sector is anything but simple.

The analyses and modelling developed are very useful tools in the public planning phase; the application to the small village of Chiaravalle made it possible to develop a potentially useful test for extending the methodology to other areas of the city, in order to highlight the actual potential of virtual energy sharing.

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References

1. A. Tatti, S. Ferroni, M. Ferrando, M. Motta, and F. Causone, The Emerging Trends of Renewable Energy Communities’ Development in Italy, **15**, 6792, (2023), https://doi.org/10.3390/su15086792
2. F. Ceglia, P. Esposito, A. Faraudello, E. Marrasso, P. Rossi, and M. Sasso, An energy, environmental, management and economic analysis of energy efficient system towards renewable energy community: The case study of multi-purpose

energy community, J. Clean. Prod., **369**, 133269, (2022), https://doi.org/10.1016/j.jclepro.2022.133269

3. A. Cielo, P. Margiaria, P. Lazzeroni, I. Mariuzzo, and M. Repetto, Renewable Energy Communities business models under the 2020 Italian regulation, J. Clean. Prod., **316**, 128217, (2021), https://doi.org/10.1016/j.jclepro.2021.128217
4. European Commission Directorate General for Energy, Clean Energy for All Europeans Package, Publ. Off. Eur. Union, (2019), https://doi.org/10.2833/9937
5. E. Caramizaru and A. Uihlein, Energy communities: an overview of energy and social innovation, Publ. Off. Eur. Union, (2020), https://doi.org/10.2760/180576
6. A. Grignani, M. Gozzellino, A. Sciullo, and D. Padovan, Community Cooperative: A New Legal Form for Enhancing Social Capital for the Development of Renewable Energy Communities in Italy, **14**, 7029, (2021), https://doi.org/10.3390/en14217029
7. European Parliament and the Council of the European Union, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast), Publ. Off. Eur. Union, (2018)
8. Camera dei Deputati; Senato della Repubblica, LEGGE 28 febbraio 2020, n. 8: Conversione in legge, con modificazioni, del decreto-legge 30 dicembre 2019, n. 162, recante disposizioni urgenti in materia di proroga di termini legislativi, di organizzazione delle pubbliche amministrazioni, nonche' di inn, Gazz. Uff. Della Repubb. Ital., 1, (2020)
9. Parlamento europeo e Consiglio dell'Unione europea, DIRETTIVA (UE) 2018/2001 DEL PARLAMENTO EUROPEO E DEL CONSIGLIO dell'11 dicembre 2018 sulla promozione dell'uso dell'energia da fonti rinnovabili, Gazz. Uff. dell'Unione Eur., 2018, **128**, (2018), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN
10. ARERA, Deliberazione 4 agosto 318/2020/R/EEL, **192**, 1, (2020), https://www.arera.it/it/docs/20/318-20.htm
11. MiSE - Ministry of Economic Development, Decreto Ministeriale 16 Settembre 2020—Individuazione della Tariffa Incentivante per la Remunerazione degli Impianti a Fonti Rinnovabili Inseriti Nelle Configurazioni Sperimentali di Autoconsumo Collettivo e Comunità Energetiche Rinnovabili, MiSE—Ministry Econ. Dev., (2020)
12. Camera dei Deputati; Senato della Repubblica, Decreto Legislativo 8 novembre 2021, n. 199, Official Gazette of Italian Republic. (2021).
13. ARERA, Deiberazione 727/2022/R/eel, "Testo Integrato Autoconsumo Diffuso," (2022), https://www.arera.it/fileadmin/allegati/docs/22/720-22.pdf
14. Ricerca sul Sistema Energetico – RSE, Orange Book 2022. Le Comunità Energetiche in Italia, Fond. Util., (2022), https://www.rse-web.it/wp-content/uploads/2022/02/OrangeBook-22-Le-Comunita-Energetiche-in-Italia-DEF.pdf
15. Ministry of the Environment and Energy Security - MaSE, Energia: MASE, pubblicato decreto CER, https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer
16. Fondazione Cariplo Bando Alternative: Al via 17 Nuove CER., https://www.fondazionecariplo.it/it/news/ambiente/bando-alternative-al-via-17-nuove-cer.html#

17. Fondazione con il SUD Bando per le Comunità Energetiche e Sociali al Sud, https://www.fondazioneconilsud.it/bando/bando-per-le-comunita-energetiche-e-sociali-al-sud/
18. iFEL Fondazione ANCI Nextappennino: Pubblicato L'avviso per la Costituzione di Comunità Energetiche Rinnovabili nelle Aree Sisma, Finanziato dal Fondo Complementare al PNRR, https://pnrrcomuni.fondazioneifel.it/bandi_public/News/329
19. Ministry of the Environment and Energy Security—MaSE Componente 2 (M2C2)—Energia Rinnovabile, Idrogeno, Rete e Mobilità Sostenibile, https://www.mite.gov.it/pagina/componente-2-m2c2-energia-rinnovabile-idrogeno-rete-e-mobilita-sostenibile
20. M. Krug, M. R. Di Nucci, M. Caldera, and E. De Luca, Mainstreaming Community Energy: Is the Renewable Energy Directive a Driver for Renewable Energy Communities in Germany and Italy?, **14**, 7181, (2022), https://doi.org/10.3390/su14127181
21. M. Ferrando et al., UBEM's archetypes improvement via data-driven occupant-related schedules randomly distributed and their impact assessment, Sustain. Cities Soc., 104164, (2022), https://doi.org/10.1016/j.scs.2022.104164
22. S. Ferroni, M. Ferrando, and F. Causone, "Environmental impact assessment of renewable energy communities: the analysis of an Italian neighbourhood," IBPSA 2023, 2775, (2023), https://doi.org/10.26868/25222708.2023.1544
23. L. Carnieletto et al., Italian prototype building models for urban scale building performance simulation, Build. Environ., **192**, 107590, (2021), https://doi.org/10.1016/j.buildenv.2021.107590
24. H. Paul Williams, Model Building in Mathematical Programming. WILEY, (2013).
25. Pyomo, https://www.pyomo.org/
26. J. D. Foster, A. M. Berry, N. Boland, and H. Waterer, Comparison of Mixed-Integer Programming and Genetic Algorithm Methods for Distributed Generation Planning, IEEE Trans. Power Syst., **29**, 833, (2014), https://doi.org/10.1109/TPWRS.2013.2287880
27. A. Cosic, M. Stadler, M. Mansoor, and M. Zellinger, Mixed-integer linear programming based optimization strategies for renewable energy communities, **237**, 121559, (2021), https://doi.org/10.1016/j.energy.2021.121559
28. D. Cremoncini, G. F. Frate, A. Bischi, and L. Ferrari, Mixed Integer Linear Program model for optimized scheduling of a vanadium redox flow battery with variable efficiencies, capacity fade, and electrolyte maintenance, J. Energy Storage, **59**, 106500, (2023), https://doi.org/10.1016/j.est.2022.106500
29. Y. Fang, S. Cho, Y. Wang, and L. He, Sensitivity Analysis and Multi-Objective Optimization of Skylight Design in the Early Design Stage, **17**, 219, (2023), https://doi.org/10.3390/en17010219
30. NRG2peers, https://www.nrg2peers.eu/