Environmental impact assessment of renewable energy communities: the analysis of an Italian neighbourhood

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Abstract

In recent years, research in renewable energy community (REC) schemes, coupling renewable energy sources and building energy efficiency, is gaining momentum. In this context, Urban Building Energy Modelling tools (UBEMs) have proved to comply with the design requirements of such schemes. However, a clear methodology exploiting UBEMs to support the design of RECs is still missing, especially for assessing the greenhouse gas (GHG) emissions associated with their specific technical configuration. Here, the REC is modelled in "urban modeling interface" (umi), one of the main bottom-up physics-based UBEMs. A building archetype approach is exploited to model the scenarios and assess embodied GHG emissions. The proposed methodology gives the possibility to investigate both the embodied and operational emissions for different REC configurations. A residential neighbourhood in Italy is selected as a case study. The results demonstrate the importance of considering building characteristics when analysing emissions reductions in energy-sharing schemes, underlining the necessity of coupling the REC design with energy retrofit interventions.

Highlights

- Physics-based UBEM applications extended to support the configuration of energy-sharing schemes
- Environmental and energy parameters are coupled to quantify the environmental impact of different technical configurations of RECs
- A quantitative evaluation procedure is presented to support decision-makers in the design of low-emission RECs
- Results demonstrate and quantify the impact of the technical configuration of the buildings on the overall environmental performance of a REC

Introduction

The development of renewable energy communities (RECs) has emerged as a promising solution to mitigate the environmental impacts of urbanization and to achieve a clean energy transition (International Energy Agency, 2021). These communities aim to reduce greenhouse gas (GHG) emissions by optimizing the use of renewable energy sources (RES) on-site and decreasing energy consumption of buildings (European Commission Directorate General for Energy, 2022). The building sector still accounts for 33% of the global energy- and process-related emissions, which are mostly related to the power generation for electricity and heat. The direct and indirect emissions coming from residential buildings only, account for more than half of this percentage (International Energy Agency, 2022). Despite the potential benefits of RECs, the effectiveness of these communities in reducing GHG emissions has not been yet fully evaluated.

At the current time, urban building energy modelling tools (UBEMs) have proved to comply with the design requirements of RECs, especially in supporting early-decision stages (Bukovszki et al., 2020). Also, they are chosen for their capability to perform dynamic energy analyses of large groups of buildings and different time resolutions. In this field, existing studies have focused on optimizing the demand-response mechanism, implementing the use of RES, and reducing energy consumption (Casalicchio et al., 2020; Manso-Burgos et al., 2022). UBEMs are used to simulate the energy performance of a group of buildings and, often, the on-site energy production from RES (Ferrando & Causone, 2020). Moreover, these tools enable designers to simulate energy retrofit scenarios of entire districts according to different technical configurations, including variations of the building envelope, heating, ventilation, and air conditioning (HVAC), lighting, and renewable energy systems. It is often hard to collect and manage data of entire districts as required to perform building energy simulations of REC schemes. For this, UBEMs often rely on archetypes to characterise the building stock (Cerezo Davila, 2017). Building archetypes, or simply archetypes, are theoretical building prototypes describing a subset of buildings with similar characteristics in the stock, through a batch of data (i.e., thermophysical characteristics of the envelope components, setting of the HVAC systems, and occupancy schedules) (Sousa Monteiro et al., 2015).

Nowadays, beyond their potential, UBEMs are rarely used to obtain evidence-based decision support in the design of REC schemes. In particular, none of these tools has been yet implemented in the research on RECs for quantitively assessing the GHG emissions associated with their specific technical configuration. This makes it difficult for designers and policy-makers to make informed decisions on the optimal configuration of RECs.

The optimal configuration of a REC can be complex, involving a trade-off between energy, economic, and environmental parameters. Generally, the economic feasibility of these projects is strictly linked to the optimisation of energy self-consumption from RES (Bianco et al., 2021). However, other parameters are

becoming influential as economic incentives are released by governments to support the implementation of these schemes, and they are country-specific. For instance, in Italy, incentives are released based on a parameter called "shared energy", which depends on an hourly estimation of energy demand and renewable energy production (Cutore et al., 2023). At the same time, the REC projects claim to be evaluated for their environmental impact, thus a quantification of the associated GHG emissions is needed.

The purpose of the present work is to investigate further applications of UBEMs, revealing the potential of these instruments for a more technical-oriented evaluation of REC projects at the early stages of design. In this sense, we explored a new procedure answering to the need for a clear method, in the initiation stage of a REC project, for the evaluation and comparison of different design scenarios, based on quantitative estimations and accounting for both energy and environmental analyses.

Specifically, this work aims to answer two main questions: (i) how can UBEMs be used to quantitatively analyse the GHG emissions associated with the configuration of a REC? And, (ii) how do different configurations of a REC affect GHG emissions? To this end, we present a new calculation procedure that exploits UBEMs to assess the environmental impact of different REC configurations. Each configuration is modelled by integrating publicly available databases with building archetypes, and based on life cycle assessment (LCA) principles. Urban modeling interface (umi) (Massachusetts Institute of Technology - Sustainable Design Lab, 2022), a bottom-up physics-based UBEM tool, is chosen for its ability to perform energy simulations of different technical configurations at the hourly resolution, as well as the embodied GHG emissions at the district scale. This allows the calculation of the parameters needed for both the economic feasibility and the environmental assessment of the REC. The energy demand from umi is combined with the simulation of RES production from a plug-in built on the same computer-aided design (CAD) backbone Rhinoceros 3D (Rhino) (McNeel & Associates, 2023), to determine the operational GHG emissions. The methodology includes the evaluation of two main REC performance indicators: energy self-consumption and shared energy. These can be calculated for each technical configuration, to provide a comprehensive and holistic analysis of the performance of the community. We proposed the use of data-driven archetypes, previously developed by (Ferrando et al., 2022) for the same geographic location and destination of use of the buildings, assigned according to the year and type of construction. Lastly, by applying the methodology to a case study, we evaluated the effectiveness of our approach, reporting the quantification of GHG emissions of the REC for different energy retrofit scenarios.

In the following section, we present a description of the proposed methodology as it is used in our study. The REC modelling section collects the application of the methodology to a case study. In results and discussion, we present the numerical results obtained, investigating the impact of buildings' characterisation represented by the archetypes. Also, we discuss the implications of different configurations on both the performance and the environmental impact of a REC. In the conclusion we underline the achievements of our study, providing the limitations and future research possibilities.

Methodology

The theoretical framework for the presented methodology is based on a combination of LCA and UBEM methods. LCA is a widely used methodology for assessing the environmental impacts of products and processes. This approach can be used to analyse both direct and indirect impacts across the entire life cycle (LC) of a building (Gervasio & Dimova, 2018). Here we adopt this method to evaluate the GHG emissions associated with the building envelope (embodied emissions) and its operation (operational emissions), to define a new calculation procedure.

UBEM is a computational approach to simulate the energy demand and performance of buildings, and it can be used to estimate the operational energy use of buildings under different hypotheses of technical configuration. In this study, the umi software is exploited to determine the annual energy use profile of the energy community with an hourly resolution and to calculate the embodied emissions of building materials. The energy production from photovoltaic (PV) panels is simulated via Ladybug (LB) (Ladybug Tools LLC, 2022) in Grasshopper, an open-source parametric design software, built in Rhino, the same CAD backbone of umi. This allows to use of the same district geometry to simulate the REC model in a single virtual environment.

In our methodology, data is collected from a variety of sources, mainly publicly available databases for GIS data, weather data, and LCA data for building materials. Building envelope properties, together with building uses profiles can be obtained either from monitoring campaigns and gathered in archetypes (Ferrando et al., 2022; Hu et al., 2021; Palmer Real et al., 2022; Pasichnyi et al., 2019), or from building-codes (O'Brien et al., 2017). These should be carefully chosen, as may lead to a misrepresentation of the district demand (Cerezo Davila, 2017). Here, we exploit data-driven archetypes developed by Ferrando et al. for the same geographic context of the case study (Ferrando et al., 2022).

Figure 1 shows the overall methodology process. The workflow consists of four main steps: the modelling in Rhino of the district environment and geometries derived from weather and GIS databases (1), the modelling and simulation in umi of the REC embodied GHG emission and energy uses exploiting data-driven building archetypes (2), the modelling and simulation of the on-site energy production from RES in LB (3), the post-process activity in Excel to combine the simulation results and calculate the total yearly emissions and the other performance indicators of the REC (4). In this process, the national legislation on RECs is used to set the configuration scenarios, by constraining the building archetypes and the energy production from RES.

In the following section, we present the application of the methodology to a case study, chosen for its consistency with the analysis purposes. The Italian neighbourhood selected in this study is a REC pilot project in the NRG2peers project (NRG2peers, 2023), a European Union-funded project under Horizon 2020. The research design involved the selection of three different configurations of a REC, with varying energy retrofit strategies and HVAC systems design. These scenarios were selected to represent realistic potential configurations for the REC and to demonstrate the flexibility and applicability of the new methodology. The technical configuration of each scenario is modelled via building archetypes. Specifically, we exploit the aforementioned data-driven archetypes to describe the state-of-the-art of the neighbourhood as a baseline. Each new configuration, representing a possible energy retrofit intervention, is developed by modifying the archetypes adopted to simulate the baseline.
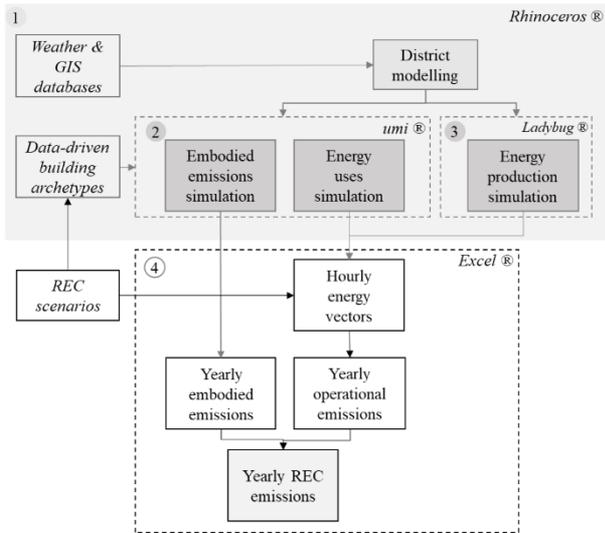
Figure 1: Schematic illustration of the proposed methodology

Overall, the new methodology represents a significant advancement in the assessment of GHG emissions associated with REC schemes and has the potential to inform policy and practice in the design and construction of low-impact communities.

REC modelling

Case study

The analyses performed and presented in this work focus on the residential neighbourhood of Chiaravalle, in Milan (Italy). The selected area is in the southern part of the city, with a total of 49 buildings. The neighbourhood's buildings range from 3 to 15 meter-height (i.e., 1 to 5 floors). Modelling the buildings in umi existing data-driven residential archetypes are used to characterise the buildings, according to the year of construction and the construction typology. The different envelope characterisations included in the archetypes come from the work of Carnieletto et al., (2021), where the construction characteristics are reported in detail. Whereas, the model is based on the work of Ferrando et

al., (2022), which contains information about the occupancy schedules and the energy demand profiles, used to represent the current state of the neighbourhood.

Energy modelling

The energy modelling started by collecting district information from publicly available databases to create the neighbourhood geometry and impose the boundary conditions on the model. In particular, here we exploited the municipal GIS data (Comune di Milano, 2023) and weather files from the EnergyPlus website (National Renewable Energy Laboratory, 2023). According to the effective Italian decree (Camera dei Deputati; Senato della Repubblica, 2021), the REC is modelled as a neighbourhood of buildings where each connection to the public grid is linked to the same medium and high-voltage cabin and where electricity from on-site RES is generated from PV systems of no more than 1MW each. On this base, a set of 3 scenarios is developed to allow the comparison among different configurations in terms of GHG emissions: a baseline and two energy retrofit scenarios. In terms of the characterisation of the buildings, the baseline consists of the current state of the neighbourhood. This scenario was developed under the hypothesis that a REC project at least requires on-site electricity generation from RES and a virtual energy sharing mechanism, based on which economic benefits are annually released to the community members. Conversely, the two retrofit scenarios are built as representative solutions for district electrification of uses, following the direction pursued by national and European policies. The scenarios were built by considering that full (100%) electrification is yet barely feasible on a large district scale. Therefore, we modelled low partial electrification (E25%) and an intense electrification scenario (E75%). Both of them include energy retrofit interventions on the neighbourhood buildings, by increasing the envelope and HVAC system performances. Table 1 reports the way each scenario is modelled in terms of the HVAC system. The retrofit scenarios are developed by simply modifying the baseline archetypes. In the E25% condensing boilers provide DHW to all buildings and heating to 75% of the buildings. The remaining 25% of heating uses are covered by air-to-air heat pumps. Similarly, the E75% scenario consists of the substitution of traditional boilers with condensing boilers. Here, boilers cover DHW and 25% of heating uses, while 75% of heating uses are addressed by air-to-air heat pumps. Specifically, the first retrofit scenario (E25%), represents a light retrofit of the neighbourhood, while the second scenario (E75%) is built to show the effect of a deep energy retrofit. The global efficiency of the boilers is set as 0.712 and 0.9, for the traditional and the condensing ones respectively. The SCOP of the heat pump is 3.5. Moreover, the GHG emission factors for natural gas at a national level are provided as kilograms of equivalent CO_2 for each standard cubic meter (ISPRA, 2021), therefore the energy use results are converted into CO_2 emissions. The conversion factor adopted to transform the kWh in smc is set as 0.095 according to the Energy

Ministry Decree (Decreto Ministeriale 21 Dicembre 2021, n. 154, 2021).

Table 1: HVAC system characterisation for each scenario

Scenario	DHW system	Heating system
Baseline	Traditional boiler	Traditional boiler
E25%	Condensing boiler	25% Heat Pump + 75% condensing boiler
E75%	Condensing boiler	75% Heat Pump + 25% condensing boiler

The retrofit strategy for the buildings' envelope is based on the current Italian building code (Regione Lombardia, 2019). Precisely, the envelope improvements of buildings in the E25% retrofit scenario reach the minimum envelope performance requirements, while in the scenario E75% the retrofit is more advanced and the envelope performances are higher (corresponding to the minimum requirements for new buildings). Table 2 reports the new thermal transmittances of the envelope components in the two retrofit scenarios. To reach the desired transmittances, a layer of expanded polystyrene (EPS) with a conductivity of 0.036 W/mK is applied to all the external envelope components, with a thickness ranging from 2 to 14 cm in scenario E25% and between 4 and 15 cm in scenario E75%. EPS insulation was chosen for coherence with the current state insulation materials and because it is the most commonly employed in retrofit interventions in the same location.

Table 2: Thermal transmittances [W/m^2K] of opaque envelope components for each retrofit scenario

Construction element	Construction name	E25%	E75%
Roof	Wooden roof/No insulation	0.233	0.219
	Reinforced brick-concrete slab	0.240	0.220
	Reinforced brick-concrete slab, traditional screed	0.240	0.220
	Reinforced brick-concrete slab, insulated (2000-2005)	0.228	0.215
	Reinforced brick-concrete slab, insulated (2005-2010)	0.231	0.217
External Wall	Stone Masonry	0.268	0.250
	Hallow wall brick masonry	0.284	0.263
	Cinder blocks with cavity	0.275	0.256
	Precast Reinforced concrete wall, low insulation (2000-2005)	0.283	0.262
	Precast reinforced-concrete wall, low insulation (2005-2010)	0.268	0.250
	Perforated bricks and medium insulated	0.265	0.246
External floor	Concrete Ground Slab	0.278	0.258
	Reinforced concrete slab, traditional screed	0.278	0.258
	Reinforced concrete slab, lightweight screed	0.278	0.258
	Reinforced concrete slab, lightweight screed, insulated (2000-2005)	0.290	0.250
	Reinforced concrete slab lightweight screed, insulated (2005-2010)	0.287	0.247

Lastly, to simulate the retrofit of the glazed envelope components, we assumed to replace the windows of all the buildings with high-performance elements. Table 3 reports the new elements together with their thermal transmittances.

Table 3: Thermal transmittances [W/m^2K] of glazed envelope components for each retrofit scenario

Scenario	Construction	U_w [W/m^2K]
E25%	Lite low-e double glazing	1.70
E75%	Cool-lite double glazing	1.13

Also, the configuration of the on-site energy production simulation is performed on the basis of the Italian effective legislation on REC schemes and modelled in Grasshopper, using the LB application. In all the scenarios, the electric energy production on-site is entirely provided by PV systems installed on the building's roofs. The PV panels are modelled in Grasshopper, using the LB module, considering all the pitched and flat roofs of the 49 buildings from the Rhino model. The PV surfaces are tilted according to the inclination of the roof surfaces, which are 26° from the horizontal plane, on average. Modelling the panels in LB, we simplified the PV system representation in two ways: (1) all the roof surfaces are considered entirely, without the real obstacles (e.g., machinery, aerials, technical rooms, etc.) present on the roofs, and shaped as regular polygons, (2) PV modules have all the same technical characteristics, corresponding to those approved by the authorities (i.e., Monuments and Fine Arts Department) in the specific district. The efficiency of the modules is 16.6 %, and the AC/DC derate factor is set as 0.976. First, 100% of the roof surface is simulated, for all the buildings, to get the maximum on-site energy production from RES of the case study. Figure 2 shows the model of the Chiaravalle neighbourhood in Rhino, with the roof surfaces (in red) evaluated for the on-site energy production simulation. The names of the buildings and the archetypes ("B1930", "B1970", "B1990", "B2005", "B2010", "A2010") assigned to each building in the model are those presented in the work of Ferrando et al., 2022.
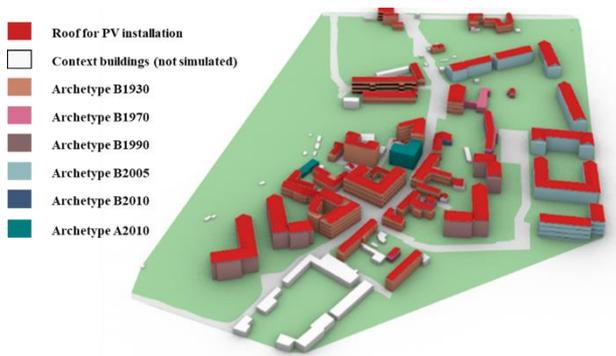
Figure 2: Illustration of the neighbourhood 3D model in Rhino

The energy simulations are run separately in the two applications, umi, and LB, to get the yearly energy uses and energy production from RES of the entire neighbourhood, with hourly resolution. Once the simulations are completed, the results are exported in a spreadsheet. Here, different scenarios of RES configuration can be inferred directly from the hourly energy production vectors. In our study, we evaluated the production potential of 15% of each roof surface, which represents a more realistic percentage of the roof surface available for the installation of PV systems.

Meanwhile, within the same umi model, the tool allows the simulation of the embodied GHG emissions, customised at the construction materials level. After the simulations are concluded, the results are processed in Excel, to evaluate the annual total GHG emissions for the specific REC configuration.

GHG emissions calculation

The evaluation of GHG emissions associated with the REC scheme includes the calculation of the operational emissions associated with energy uses and the emissions embodied in the building construction. In the proposed methodology the embodied emissions are calculated for the current state of the building's envelope and, in the retrofit scenarios, adding the new envelope components designed for each scenario. As the REC configuration is generally performed on existing buildings, our analysis compares different configurations for a REC, starting from the current state of the neighbourhood. To this end, in the calculation of the embodied GHG emissions, the components of the existing buildings account for the "gate-to-cradle" (from usage to the end of life) portion of emissions. The new components, present in the retrofit scenarios, are instead evaluated for their impact in all the LCA stages, from cradle-to-grave. Embodied carbon is a subjective topic and depends on the region (Khan et al., 2022). Therefore, in our work, we used the Oneclick LCA library, which is based on the Ecoinvent Background database (Ecoinvent Database, 2023) to determine the materials' GHG emissions, for each LCA stage, according to the specific geographic location. Also, a life span of 50 years is considered.

The operational emissions are calculated from the results of the energy simulations, using the energy that uses the net of PV production. In particular, we exploited national

GHG emission factors, which reflect the emissions related to the importation and production of each carrier in a specific country. In this case, we adopted the latest factors released by the Italian government. According to the National Inventory Report 2021 (NIR) (ISPRA, 2021) the carbon emissions related to natural gas are equal to 1.976 $kgCO_2$/smc. To this value, we added the emissions of other two GHGs used in the LCA global warming potential evaluation: Methane (CH_4) and Nitrous oxide (N_2O), respectively 0.00099 $kgCO_{2\text{-eq}}$/smc and 0.0028 $kgCO_{2\text{-eq}}$/smc. The emissions for the electric consumption estimated for 2021 by the NIR are 0.2457 $kgCO_{2\text{-eq}}$/kWh.

REC performance indicators

After the GHG emissions are calculated, the performance indicators can be compared to produce a more accurate evaluation of the REC configuration.

The self-consumption is calculated as the yearly sum of all the hourly differences between the electric energy use and the PV production of the REC (Bianco et al., 2021).

The shared energy is the hourly minimum between the net energy fed into the grid and the energy taken from the grid (Cutore et al., 2023). In this case, the net is considered as the net of the PV production. However, due to technical and legislative constraints, a direct self-consumption is not always possible. Therefore, here, to be conservative, the calculation of the shared energy is performed considering the gross energy taken from the grid.

Results and discussion

In this section, we present the results of the analysis of GHG emissions associated with three different configurations of a REC. We first discuss the embodied emissions associated with each configuration, followed by a discussion of operational emissions. The building typology has a strong influence on the life cycle performance of the building (Gervasio & Dimova, 2018). To better understand the impact of the technical configurations of the buildings in the REC design, we grouped the 49 buildings based on their characteristics. The groups were determined by the archetypes sharing the same building envelope properties and HVAC system settings. Hence, the buildings are grouped into six clusters, according to the archetype range of construction years: before 1930 (B1930), 1930 - 1969 (B1970), 1970 - 1989 (B1990), 1990 -2004 (B2005), 2005 – 2009 (B2010), 2010 and after (A2010). The archetypes' characterisation is presented in the work of Ferrando et al., 2022. In the same work, the accuracy of this modelling technique is discussed, for the same district model, presenting the variation of the root means square error of the simulations.

Embodied emissions

Figure 3 presents the embodied GHG emissions associated with each configuration of the REC grouped according to the archetypes. The emissions are reported as the normalised yearly GHG emissions per square meter of the building's gross floor area, considering a lifespan of 50 years. The results show that emissions are higher for configurations with advanced energy retrofit. This reflects

the impact of adding a new insulation layer in each envelope component. The use of EPS insulation in the newest building archetypes increases the associated GHG emissions. Polymeric insulations have high associated emissions in the waste disposal LCA stage. PVC products incineration emits 2.07 $kgCO_{2-eq}$ for each kilogram of product, far from the order of magnitude of the emissions for the waste treatment of other insulation materials (i.e., natural fibres emit about 0.002 $kgCO_{2-eq}$/kg).
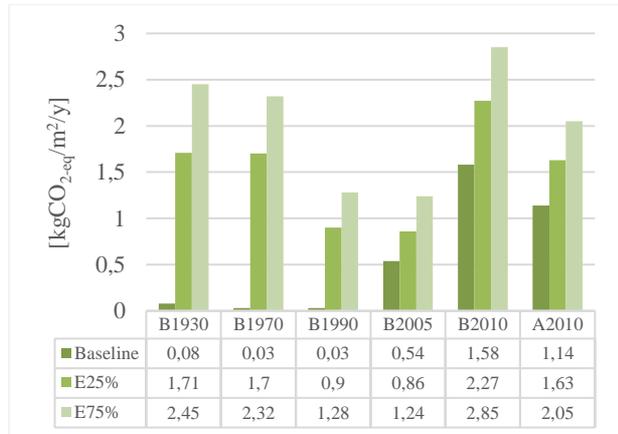
Figure 3: Embodied emissions for each archetype in the REC [$kgCO_{2-eq}/m^2/y$]

The last three archetypes, B2005-A2010, registered the smallest increase of emissions both from the baseline scenario to the E25%, and from the E25% to the E75%. Here, the impact of the retrofit in terms of embodied emissions is low, as they are characterised by envelope components already including EPS insulation layers.

Operational emissions

To evaluate the operational emissions we used the results of the energy simulations conducted in umi and LB. Figure 4 shows the results of our analysis, in terms of yearly operational GHG emissions per square meter of the building's gross floor area. The trend of the baseline results is descending, from the oldest construction type to the latest. The buildings in the archetype "A2010" reported the lowest average GHG emissions per square meter. These are buildings characterized by higher energy performances and lower energy use densities, compared to the other buildings. The trend changes in the energy retrofit scenarios, where the differences among all the archetypes are lowered, except for the "A2010", outstanding from the trend in all the analysed scenarios. The energy uses are strictly linked to the energy performance of the envelope and the envelope components of all the buildings in each retrofit scenario are brought to similar values. Also, the introduction of more efficient HVAC systems lowered the energy use for all the neighbourhood buildings. These actions, combined with the electrification of uses proposed in the retrofit decrease the operational emissions.
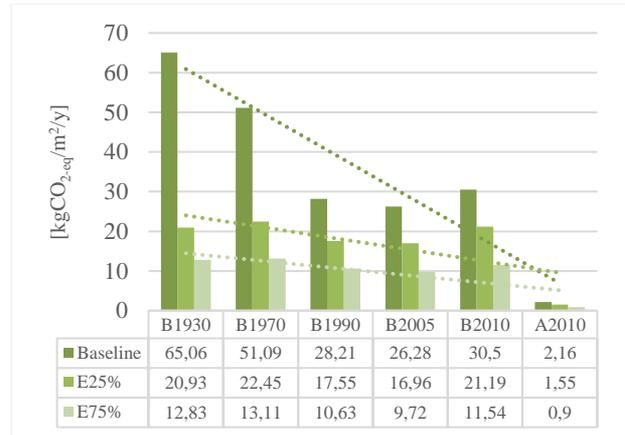
Figure 4: Operational emissions for each archetype in the REC [$kgCO_{2-eq}/m^2/y$]

According to Gervasio & Dimova, 2018, the average operational GHG emissions of residential buildings generally vary between 30 – 90 $kgCO_{2-eq}/m^2/y$. Here the minimum average values are lower in almost all the scenarios, because of the impact of on-site energy production, decreasing the emissions due to the electricity use, especially in the advance retrofit scenario E75%.

Table 4 reports the yearly GHG emissions of the REC expressed as equivalent tons of CO2. These results indicate that the technical configuration of a REC has a significant impact on the overall GHG emissions. Compared to the baseline scenario, the improved efficiency scenarios, E25%, and E75% reduced the operational emissions respectively by 57% and 68%. Conversely, both the retrofit scenarios resulted in higher embodied emissions than the baseline. However, these account only for 0.05% of the overall GHG emissions in the baseline, 6% in the E25% scenario, and 12% in the E75%. This suggests that efforts to improve building efficiency and implement RES can help reduce the GHG emissions associated with a REC configuration.

Table 4: Operational and embodied GHG emissions of the whole neighbourhood [$tonCO_{2-eq}/y$]

GHG emissions	Baseline	E25%	E75%
Operational	2426.0	1044.7	764.9
Embodied	14.4	71.8	102.2
Total	2440.4	1116.5	867.1

Figure 5 summarises the results of the analysis for each archetype and each REC configuration. A box plot was adopted to visualise the variations in the GHG emissions results occurring among buildings with similar technical configurations. Buildings characterised by older construction types show the highest variation among the results. These categories are populated with the highest number of buildings. Also, the impact of the poor energy performance of the building envelope is lower compared to the parameters affecting the building energy uses (i.e., building orientation, and internal loads). This was confirmed by the results obtained for the embodied and operational emissions separately. These results reflect the

variation reported for the operational results, rather than the embodied.
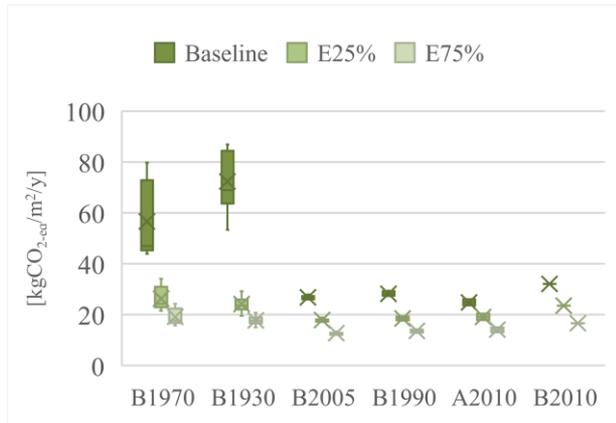
Figure 5: Overall GHG emissions for each archetype in the REC [kgCO$_{2-eq}$/m^2/y]

The results were compared with other studies. I.e., according to the JRC "Environmental Benchmarks for Buildings" 2018 (Gervasio & Dimova, 2018), GHG emissions associated with residential buildings vary between 50 – 230 kgCO$_{2-eq}$/m^2/y. Here the values are lower. On one side, this is reasonably due to on-site RES energy production, reducing the emissions related to electricity consumption in all the categories and scenarios. On the other side, due to the assumptions made for the system boundaries of existing buildings in the embodied emissions calculation, the embodied results are significantly lower than the ones calculated in other studies (Gervasio & Dimova, 2018, Rasmussen, F. N. et al., 2019, Simonen et al., 2017,), which consider the whole life cycle stages of residential buildings.

To fully evaluate the performance of each configuration, two performance indicators were evaluated. Table 5 reported the yearly self-consumption and shared energy in MW per square meter of the building's gross floor area, together with the GHG emissions results. The two indicators show an ascendent trend according to the increase of energy performance of the buildings, and a descendent trend in the GHG emissions. Compared to the baseline, the retrofit E25% and E75% report an increase of respectively 2% and 4% in self-consumption, and of 15% and 41% in shared energy. At the same time, the two retrofit scenarios reached a reduction of 54% (E25%) and 64% (E75%) of GHG emissions.

Table 5: HVAC system characterisation for each scenario

Parameter	Baseline	E25%	E75%
GHG emissions [tonCO$_{2-eq}$/y]	2440.4	1116.5	867.1
Self-Consumption [MWh/y]	328.3	334.5	342.7
Shared Energy [MWh/y]	672.6	770.5	951.5

Conclusion

In this study, we developed a new calculation approach to quantify the embodied and operational GHG associated with RECs, using UBEMs. Our approach provides a detailed breakdown of the GHG emissions according to a REC configuration. Also, it allows the comparison of the results in terms of REC performance indicators, for different configurations. The work clearly demonstrates the potential application of UBEMs in the research on RECs, accounting for both energy and environmental analyses.

Further, our results show that the technical configuration of buildings within a REC can have a significant impact on emissions reductions. An advanced energy retrofit of the building envelope and the use of heat pumps for a large portion of heating energy needs can lead to significant reductions in GHG compared to the state-of-the-art building envelope and traditional boilers.

The analyses also demonstrate the importance of building characterisation when analysing emissions reductions in RECs. We found that buildings with similar characteristics tended to have similar operational emissions. At the same time, the advanced efficiency scenario resulted in the lowest emissions per square meter of building floor area across all building archetypes. The results, also, suggest that efforts to develop and implement advanced efficiency measures could be an effective strategy for reducing GHG emissions and, simultaneously, increasing the performance of REC.

These findings can inform the development of policies and regulations aimed at promoting the construction of sustainable and energy-efficient communities.

Further developments of the present work could include (i) the evaluation of different envelope characterisation and HVAC systems in the retrofit scenarios to quantitatively assess the impact of specific energy retrofit solutions, also differentiating among the buildings' potential on-site energy production, (ii) the calculation of the GHG emissions associated with PV and HVAC systems to refine the evaluation of the embodied emissions, (iii) the incorporation of other LCA impact categories within the environmental impact assessment.

Generally, it can be worthed to apply the same procedure to a multitude of different case studies, investigating further the relationship between the performance of a REC and the GHG emissions.

Acknowledgement

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