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Towards a Low Carbon Future: Evaluating Scenarios for an Energy Community through a Multi-Objective Optimisation Approach

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Abstract:

Several literature works have highlighted that the expansion of electrification across all sectors is a crucial factor in promoting the transition of energy systems towards carbon neutrality by mid-century. However, polygeneration systems through the appropriate integration of different renewable energy sources are expected to play an important role in such transition by effectively reducing the total primary energy demand, as explored in the present work for an energy community (EC) case study. Therefore, this paper presents the optimal synthesis, design, and operation of an EC system working under three different scenarios and evaluates the trade-offs between the total annual costs and greenhouse gas (GHG) emissions (evaluated as CO_2 equivalent emissions). The EC is a District Heating and Cooling Network (DHCN) composed of nine third sector buildings in the northeast of Italy. The DHCN superstructure includes several possible energy supply components for each EC member, a central unit, and heat and/or cooling connections between buildings. Moreover, peer-to-peer electricity sharing is allowed among EC members, through a local electricity grid, before buying/selling electricity from/to the main grid. The superstructure was optimised through a mixed integer linear programming (MILP) model considering a multi-objective optimisation for the total annual cost (for owning, operating, and maintaining the entire system) and the total annual CO_2eq emissions as the objective functions. The three scenarios through which the EC system is optimized and evaluated consider the type of consumed gas (natural gas or biomethane) and the electricity consumption configuration (on-grid or off-grid). Results have shown that the cost (per ton of CO_2eq) to reduce emissions is too high if the European Union's carbon market is considered. This was especially critic for the natural gas scenario, where the cost per ton of CO_2eq (between two optimal solutions) was about four times higher than its cost on carbon market.

Keywords:

Polygeneration systems; Renewable energy sources; Energy community; Carbon neutrality; Multi-objective optimisation.

1. Introduction

The 2021/2022 global energy crisis was essentially the consequence from two main worldwide problems regarding primary energy: supply and prices. According to a report by IEA [1], such problems were ignited by several factors, including the economic recovery that started to take place as the Covid-19 pandemic progressively weakened in 2021 and the beginning of Russia/Ukraine war in February 2022. The result was a brutal energy prices increase [2] in comparison with pre-pandemic levels, followed by a substantial coal consumption growth [3]. The European Union (EU), deeply affected by a plunge in Russian's gas supply, released a report [4] with a set of actions to avoid gas shortages in 2023 such as energy efficiency improvements of industries, and public and private buildings, deployment of renewables, and electrification of heat.

The aforementioned context has highlighted the ever importance of primary energy savings. Among the main solutions the scientific community has developed, energy communities have arisen as an advantageous way for energy savings in different types of buildings. In a recent work [5], our research group

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studied the design and operation of an energy community (EC), comprising nine tertiary sector buildings, for a city in the northeast of Italy. Besides a reduction in total costs and CO_2eq emissions, the implementation of peer-to-peer electricity sharing within the EC demonstrated the possibility of saving primary energy (natural gas, in this case) since the cogenerated and shared electricity among the EC members allows a substantial reduction in the total amount of electricity imported from the main electric grid. It is possible to find in literature not only other works dealing with EC optimisation for tertiary sector buildings [6], but also studies focused essentially on the same kind of work but aiming residential, commercial, and industrial buildings [7-10].

In addition to primary energy savings, the report from EU [4] highlights also the importance of deploying renewables. This is a key concern for EU since it has fixed deadlines, through different pieces of legislation, to reach carbon neutrality by 2050. For instance, the EU 2030 target plan [11] aims a more ambitious and cost-effective direction to reach the carbon neutrality by 2050, without forgetting the encouragement for creating new green jobs and for stimulating international partners to also increase their carbon neutrality ambitious. As a part of the EU 2030 target plan, the so called "Fit for 55" package [12] proposes an ambitious target for decreasing the net greenhouse gas (GHG) emissions by at least 55% (of the 1990 net GHG emissions level) by 2030. According to the EU council [13], the package aims to create a balanced and coherent framework for attaining the EU's climate goals, while ensuring a just and equitable transition, promoting innovation and competitiveness of EU industry, and maintaining a level playing field with third country economic operators. Still according to them, to accomplish these goals, member states must implement concrete measures to decarbonize their economies, and the "Fit for 55" package provides legislative proposals and amendments to assist in achieving this objective.

Figure 1. Categories included in the "Fit for 55" package [12].

The "Fit for 55" package describes also, in detail, how the EU will translate its climate goals into legislation. Specific categories (Fig. 1) will give directives that include energy taxation, energy-efficient transition, reform to the EU emissions trading system, energy performance of buildings, and boost of renewable energy sources. For instance, the directive regarding energy-efficient transition [14] claims that energy saving is the most cost-effective solution for reaching the climate goals in the energy sector. Indeed, with such a solution it is possible to reduce lots of GHG emissions besides providing more affordable energy. In the same line, the directive for boosting renewable energy sources [15] says that moving towards such energy sources the GHG emissions will be substantially reduced while the human health and air quality will be improved. Different studies regarding improvement of energy communities have already analysed the agreement of their results with the "Fit for 55" package [16] or, at least mentioned their awareness and importance of such piece of legislation [17,18].

From the depicted literature review, one can verify the attention that the scientific community has given to enhancing energy communities' performance. Moreover, it is also possible to verify the attention that the EU has given on the reduction of net GHG emissions by 2050. Such EC improvements aim not only to achieve lower costs and emissions but also lower levels of primary energy consumption (in line with the European Union report [4]). In agreement with these issues, this work aims to conduct an analysis of different scenarios in order to evaluate the performance of an EC (located in Pordenone, northeast of Italy) comprising nine buildings from the third sector and working with natural gas or biomethane, as one of the input energy vectors. For each one of these fuels, the EC behaviour will be assessed when it is connected or not to the electricity grid. The evaluation will be made through a multi-objective optimisation (total annual costs and CO_2eq emissions) using a mixed integer linear programming (MILP) model that evaluates the optimal solution regarding the synthesis, design, and operation of the specified superstructure for the EC. The energy system structure for each building is optimised individually, in accordance with its energy demand. The district heating network (DHN) and the district cooling network (DCN) are also optimised, i.e., depending on the energy demand of each building and the distance between them, the pipelines network is also optimised in accordance with the energy system structure of each building. Besides heating and cooling, peer-to-peer electricity sharing is also allowed in the community, which gives the EC a lower dependency on the electric grid or even the possibility to be off-grid.

2. DHCN superstructure

The superstructure shown in Figure 2 is comprised of three main subdivisions. The first one is the Polygeneration Unit k, which is a set of equipment assigned to a specific user building (referred to as "User Building k"). The second subdivision is the central unit, an independent structure that provides heating and electricity to the energy community. The third subdivision is "User i", which represents the remaining buildings within the energy community. These three subdivisions are linked through the DHCN for thermal energy exchange and the distribution substation (DS), which serves as an electricity hub. The model optimizes the pipeline connections between buildings and central unit. Rather than being connected directly to the electricity grid, all buildings and the central unit are connected to the DS, which manages the flow of electricity for all three subdivisions. This means that based on an electricity balance, the DS can:

- distribute electricity to a building, if their Polygeneration Unit cannot meet their demand,
- receive electricity from a building, if it has an electricity surplus,
- purchase electricity from the grid, if the surplus from all buildings is insufficient, and
- sell electricity to the grid, if there is a surplus and all buildings demands have been met.

For a more detailed description about all internal energy flows among components, the reader may refer to our previous work [5].

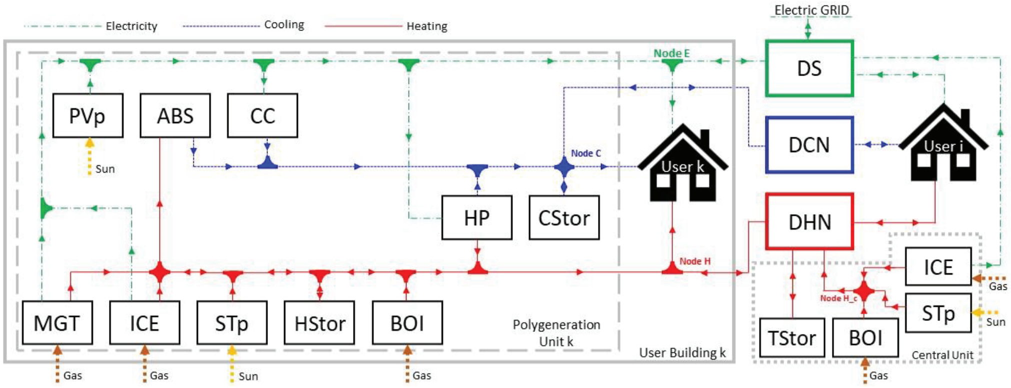

Figure 2. Superstructure of the energy community [5].

3. Model description

The optimal synthesis, design, and operation of the EC showed in Fig. 1 were defined using Mixed Integer Linear Programming (MILP) optimisation method, which involves decision variables, constraints, and objective functions. Decision variables can be binary or continuous and determine the selection, on/off status, and sizing of equipment. Constraints determine the model's limitations in terms of equipment size, performance, and energy balance, while objective functions aim to minimize predefined targets. A flow diagram of the inputs, outputs, and the core characteristics of the model can be found in Fig. 3.

The sizes of some devices, such as MGT, ICE, ABS, and HP, are predetermined, while others (BOI and CC) are left free to optimize their installation and sizes. ABS devices are only allowed to be fed by cogeneration systems and STp. The partial load performance of cogeneration systems is represented by linear relations obtained through a linear regression of their characteristic load curves. PVp and STp production data consider local hourly insolation obtained through a dedicated software [20], and the size of these solar technologies is limited to a maximum of 200 m^2 per building. The HP modelling is more complex than other devices, as the heating and cooling production cannot happen at the same time and considers both the heating and cooling demands of each EC building.

The DHCN pipelines layout and capacity are also optimised by considering the geographical location of the buildings and the distances between each other. Thermal losses are expressed by an equation that depends on the pipeline length and a coefficient of proportionality. A constraint does not allow the model to connect two users with two pipelines sending heating or cooling energy at the same time. The maximum heat flow rate is constrained by the pipelines size, and the energy flow into each pipeline is bounded between a lower and upper limit. The optimisation of the DHCN is important to minimize thermal losses through pipelines and ensure efficient energy distribution.

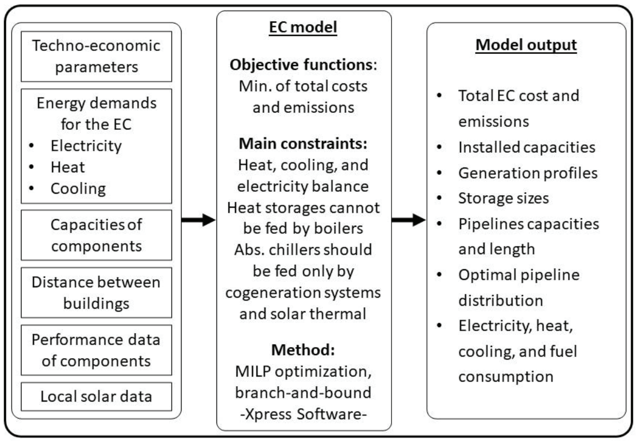

Figure 3. Flow diagram from main inputs to main outputs.

Thermal storages systems are implemented to overcome the intermittence and scarcity of sunlight during winter and, combined with cogeneration devices, to reduce the usage of backup boilers. In this way, fuel consumption and environmental impacts can be mitigated. The proposed thermal storage models provide a means of calculating the energy stored and the energy balance within them, considering thermal loss and energy input from the DHCN pipelines. These models describe the storage of thermal energy for the entire year, without time decomposition, and the connection between hours, days, weeks, and months for a whole year representation.

Energy balances are used to model the heating, cooling, and electricity constraints of the system, which are applied for the individual buildings, the central unit, and the distribution substation. The EC buildings require all three types of energy balances, which are applied at specific nodes for each type of energy. The central unit requires only the heating balance, as its electricity production is sent directly to the DS, which is responsible for managing the peer-to-peer electricity sharing among buildings.

The peer-to-peer electricity sharing methodology is implemented with the aim to reduce the amount of electricity exchanged with the electric grid, which can reduce overall costs and environmental impacts. The methodology involves the local production of electricity by each EC member and, in the case of surplus, send the overbalance to the DS to distribute it for other EC members or selling it to the electric grid. The proposed methodology has the potential to benefit EC members by reducing their reliance on the electric grid and promoting a more sustainable use of energy.

For this work, a multi-objective optimisation problem was defined to minimize the total annual cost and CO_2eq emissions. The total annual cost includes investment, maintenance, and operation costs, while the total annual CO_2eq emissions are related to the net electric energy received from the grid and the fuel consumption by boilers and cogeneration energy systems. The two objectives are conflicting, as adopting environmental efficient energy systems is costly and the solution that allows for minimum annual cost does not necessarily result in minimum total annual CO_2eq emissions. The ε-constrained method [21] is used to obtain the Pareto front solutions. The method involves identifying a set of intermediate emission levels and introducing each level as an additional constraint in further economic optimisation (it could be carried out in the other way around, i.e., performing an emissions optimisation while setting intermediate values for cost). The method allows decision-makers to explore the trade-offs between different solutions and identify the optimal trade-off between economic and environmental objectives.

For a more detailed description of the model, the reader may refer to our previous work [5].

4. Case study

The case study is an EC designed for the city of Pordenone, northeast of Italy, which provides heat, cooling, and electricity to nine different buildings: town hall, hospital, library, primary school, secondary school, retirement home, theatre, town hall archive, and a private swimming pool (Fig. 4). This study is based on a mathematical model that divides the year into 24 typical days (two typical days/month – working and non-working) of 24 hours each and calculates the optimal design and operation for the entire EC system based on the energy demand data of each building. The heterogeneous mix of buildings with different energy demands ensured that the results obtained were not biased towards a specific user profile. Furthermore, this mix of users is expected to be representative of many other small and medium-size towns in Europe.

As an example, Figure 5 illustrates the energy demand patterns of the hospital during winter and summer, based on two representative working days. During winter, the hospital exhibits a higher demand for electric energy during daylight hours, attributed to a higher occupancy factor. Additionally, there is a higher heating demand during morning and evening periods, and minimal cooling demand. Conversely, during summer, the hospital experiences a higher cooling demand, with the peak occurring around 2 p.m. The electric energy demand is similar to that of the winter season. Notably, comparing to the winter curve, the heat demand during summer is reduced by a factor between 2 and 3, as the hospital still have a high demand for sanitary water. It is noteworthy that the energy patterns of each building vary based on several factors, including occupancy factor, thermal insulation, and night lighting.

Selecting appropriate and proportionate equipment for the energy structure of the EC system is key to ensure its effective integration. The equipment should be capable of fulfilling the energy requirements of the buildings while maintaining compatibility with the system. The optimisation process involves considering two types of components, namely fixed and variable size, both of which are commercially available. The optimal size and configuration of the energy system can be achieved by determining the number of installed fixed size equipment and the size of variable size components including boilers, compression chillers, and thermal storages.

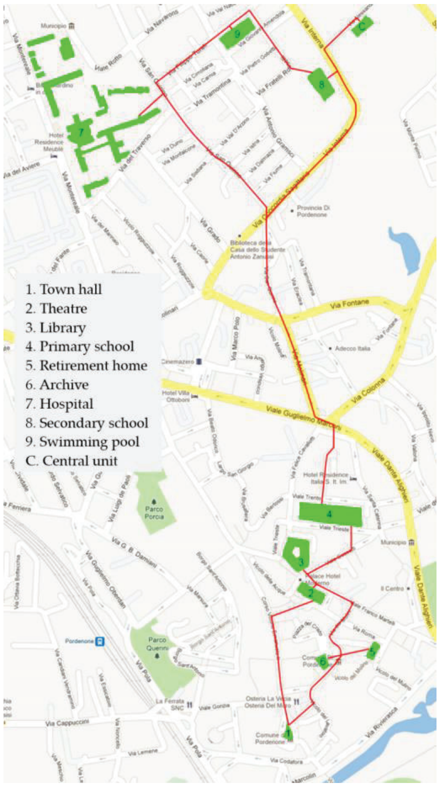

Figure 4. DHCN pipelines superstructure [5].

The interest rate is assumed to be 5%, while lifespan is determined to be 30 years for DHCN, 20 years for PV, ST panels, and TS, 15 years for ICE, MGT, ABS, and HP, and 10 years for BOI and CC. Operation costs are also considered, which include fuel and electricity costs. The price of natural gas, biomethane, purchased electricity, and sold electricity are introduced in the next section and specified for different scenarios. CO_2eq emissions related to electricity, natural gas, and biomethane consumption are taken from literature. Electricity carbon intensity was assumed to be 0.356 $kgCO_2eq/kWh$, natural gas carbon intensity 0.202 $kgCO_2eq/kWh$ [5], while biomethane was assumed to produce zero net emissions [22] as the considered CO_2eq emissions for this work are only the ones related to the energy resources.

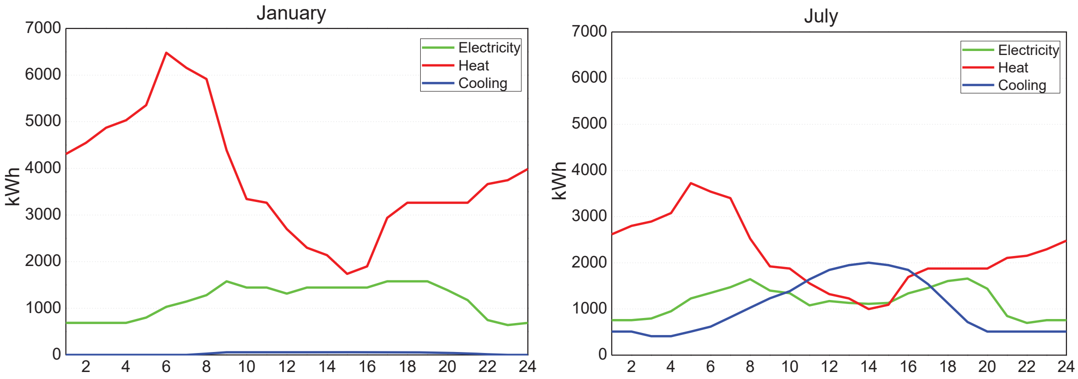

Figure 5. Hospital demands for working days of January and July.

5. Results and discussion

In order to have a reference case, a conventional solution (CS) scenario is designed, which reflects the current reality in most cases. In this scenario, electricity is obtained from the electric grid, while a local boiler (BOI) and a local compression chiller (CC) are used to meet heating and cooling demands, respectively. Heat and cooling storage systems were also taken into account to support the BOI and CC. In this case, there is no connection between the buildings, which means that there are neither DHCN pipelines linking them nor peer-to-peer electricity sharing. For a detailed CS schematic diagram, the reader may refer to reference [5]. In this scenario and for all the nine buildings combined, the total annual cost was 4370.7 k€/y while the total annual emissions were 11,281.2 ton/y. These results are considered as the references to calculate the potential decrease in total costs and emissions.

For this work, a multi-objective optimisation of the EC was conducted considering the following scenarios:

- Scenario 1: Grid-connected - natural gas consumption
- Scenario 2: Grid-connected - biomethane consumption
- Scenario 3: Grid-isolated

In line with the “Fit for 55” package from the EU [12], these scenarios have, as the main objectives, the reduction of the total annual CO_2eq emissions from the CS scenario, while reducing also the total annual costs. The Grid-connected scenario means that the EC is allowed to buy electricity from the national grid at 170 €/MWh and to sell it, also to the national grid, at 100 €/MWh [5]. The difference between these two scenarios is that they are analysed also for two types of gas consumption: natural gas or biomethane. For this work, no proportion between them was considered for any of the scenarios. The purchase price for gas was dependent on the type of consumption: for CHP equipment or for boilers. For the scenario with natural gas consumption, the purchase price was 45 €/MWh (CHP) and 60 €/MWh (boilers) [5]. For the scenario with biomethane utilization, the purchase price was 52 €/MWh (CHP) and 70 €/MWh (boilers) [19].

5.1. Scenario 1: Grid-connected – natural gas consumption

Figure 6 shows the Pareto curve for scenario 1 and the comparison with the CS scenario. Tables 1, 2, and 3 present, respectively, the configurations for each building for points A, B, and C in the Pareto curve. Point A represents the optimal economic optimisation solution, point C represents the optimal emissions optimisation solution, while point B represents the optimisation solution which has the same emissions level as point C, but with 68.5% of the cost.

In the comparison between scenario 1 and CS scenario, one can observe that the lowest reduction in CO_2eq emissions was obtained for point A (optimal economic solution), which resulted in 34% less CO_2eq production. For the comparison between CS scenario and the optimal emissions solution (point C), the CO_2eq emission reduction was 51%. However, very similar level of reduction can be reached through the trade-off solution represented by point B, i.e., with a decrease of 31.5% on the total annual costs (which represents 1307.3 k€/y), the EC will still emit around half of the emissions resulted from the CS scenario. Such a fact can be explained by the amount of equipment installed by the solution in point C (Table 3). As the simulation, in this case, is not worried about costs, it will find a solution that has minimum emissions no matter how many components would have to be installed. One of the main characteristics of the model is that the economic sub-model is relatively more complex than the one for emissions. Therefore, when reducing emissions is the only target, the simulation will not do further calculations once it has found the optimal solution. Another plausible point of view for the results presented in Fig. 6 is a comparison between point A and B. The obtained results show that an increment in economic cost of 24.5% is capable of reducing the total CO_2eq emissions by 26%. Assuming point B as the best trade-off solution, the results regarding scenario 1 have demonstrated that the EC has the potential of cutting emissions by 51% (representing almost 5800 ton of CO_2eq/y) while reducing costs by 35% (representing savings around 1530 k€/y), when compared to CS scenario.

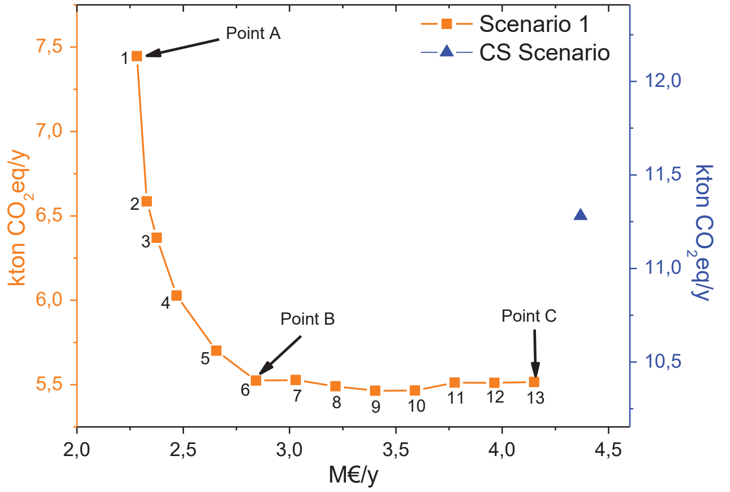

Figure 6. Pareto curve for scenario 1 and CS scenario data.

By analysing Tables 1 and 2 from the point of view of the communication between the EC and the national electric grid, it is possible to reveal some insights. The total electricity purchased by the EC was 1.18 MWh and 8168 MWh, while the total electricity sold by the EC was 3049.8 MWh and 819.1 MWh, for the optimal solutions from point A and B, respectively. Point A, which is the optimal economic solution, bought way less electricity and sold considerably more electricity compared to point B, i.e., the system of point A tried to compensate expenses related to investment, operation, and maintenance costs by selling more electricity. Moreover, the solution in point B installed 15% less engines (ICE), two thirds of heating storage (HST), one third of cooling storage (CST), and installed 43 times more solar thermal panels (ST), when compared to point A. Also, solution from point B installed around 50% more heat pumps (HP) and compression chillers (CC), which explains the higher level of electricity bought and the lower installed capacity of absorption chillers (ABS) (which is coherent with the lower installed capacities for ICE). In summary, point B saved emissions with respect to point A by consuming considerably less natural gas.

Table 1. Scenario 1: optimal economic solution (point A).

Building	ICE [kW]	MGT [kW]	BOI [kW]	ABS [kW]	HP [kW]	CC [kW]	PV [m^2]	ST [m^2]	HST [kWh]	CST [kWh]
1	70	0	0	0	70	65	0	0	1094	753
2	840	0	0	315	0	0	0	0	4000	2236
3	0	0	0	0	0	72	0	0	0	467
4	0	0	0	0	0	0	0	0	0	0
5	0	0	14	0	0	4	0	13	57	354
6	0	0	28	0	0	10	0	15	154	467
7	1200	0	0	525	420	68	0	0	4000	2185
8	420	0	0	0	0	0	0	0	115	0
9	280	0	0	0	0	0	0	0	1453	0

Table 2. Scenario 1: optimal trade-off solution (point B).

Building	ICE [kW]	MGT [kW]	BOI [kW]	ABS [kW]	HP [kW]	CC [kW]	PV [m^2]	ST [m^2]	HST [kWh]	CST [kWh]
1	0	0	0	70	0	0	0	200	568	183
2	420	0	0	105	0	0	0	200	1152	51
3	0	0	20	0	105	77	0	53	206	297
4	50	0	0	0	0	0	0	0	2	0
5	0	0	0	35	35	23	0	188	558	238
6	0	0	0	35	0	33	0	178	506	61
7	1200	0	60	105	630	208	0	200	3118	952
8	0	0	0	0	0	0	0	0	0	0
9	700	0	0	105	0	0	0	200	728	0

Table 3. Scenario 1: optimal emissions solution (point C).

Building	ICE [kW]	MGT [kW]	BOI [kW]	ABS [kW]	HP [kW]	CC [kW]	PV [m^2]	ST [m^2]	HST [kWh]	CST [kWh]
1	420	390	0	420	420	72	0	200	4000	4000
2	840	600	0	630	630	379	0	200	4000	4000
3	300	180	241	210	210	0	0	200	4000	4000
4	300	180	129	210	210	0	0	200	4000	4000
5	300	180	0	210	210	40	0	200	4000	4000
6	300	180	0	210	210	15	0	200	4000	4000
7	1200	1200	1626	630	630	77	0	200	4000	4000
8	420	390	0	420	420	0	0	200	4000	4000
9	840	600	0	630	630	0	0	200	4000	4000

5.2. Scenario 2: Grid-connected – biomethane consumption

In agreement with the EU 2030 target plan [11] for a more ambitious and cost-effective direction to reach the carbon neutrality by 2050, this section has been thought as a possible scenario to help EU achieving its environmental goals.

By picturing scenarios where the proportion of biomethane in the natural gas grid is increasingly higher, it is reasonable to infer that emissions in scenario 1 would be increasingly lower (biomethane has been considered a net-zero CO_2eq emitter [22]). From this point of view and considering the limit case of a natural gas grid in which its methane content is completely replaced by biomethane, this work analysed the EC compared not only with the CS scenario, but also with scenario 1.

Figure 7 shows the Pareto curve for scenario 2, while Table 4 shows each building configurations for points D, in the Pareto curve, which represents the optimal economic solution. The first reasonable comparison is between points A and D (Figs. 6 and 7), which represent the optimal economic solutions for scenarios 1 and 2. The total annual costs for these solutions were, respectively, 2282.1 k€/y and 2587.8 k€/y, while the correspondent CO_2eq emissions were 7446.4 ton of CO_2eq/y and -457.1 ton of CO_2eq/y. Therefore, one can observe that an increase of 13.4% in the total annual costs (around 305.7 k€/y) allowed a reduction of 106% in the total annual CO_2eq emissions, which means that the emissions were cut off and then compensated by almost 460 ton of CO_2eq/y. This happened due to the CO_2eq emissions compensation when electricity is sold to the national electric grid. Although the total electricity sold in solution of point A was more than 2 times higher than that of point D, the fact that the biomethane emits way less CO_2eq than natural gas (net-zero for this work) has contributed for the dominance of the electricity compensation. By comparing Tables 1 and 4, it is possible to observe that, besides buying less electricity from the national grid, the solution of point D installed 10% less engines (ICE). To compensate the missing heat production, boilers (BOI) installed capacity for point D was more than five times higher with respect to point A. Also, solar thermal panels (ST) installed capacity for point D was more than three times higher than that of point A, which reflects the search of the model for more economical solutions.

Another reasonable comparison would be between points B and D (Figs. 6 and 7). As explained in section 5.1, point B represents the selected trade-off solution for scenario 1. The total annual cost for that solution was 2842.4 k€/y, while the total annual emissions 5523.5 ton of CO_2eq/y. In this case, there were reductions for both the costs (-9%) and emissions (-108%). Regarding emissions, the same thing happened as for the comparison between points A and D, i.e., emissions were cut off and compensated by the dominance of the electricity sold. As can be observed from Tables 2 and 4, the reduction on costs (around 255 k€/y) were due to a substantial reduction of installed CC and ST. They were reduced, respectively, by 13 and 15 times from solution in point B to the one in point D. As a way to compensate this reduction, it was installed three times more BOI, two times more ABS, and four times more cooling storage (CST).

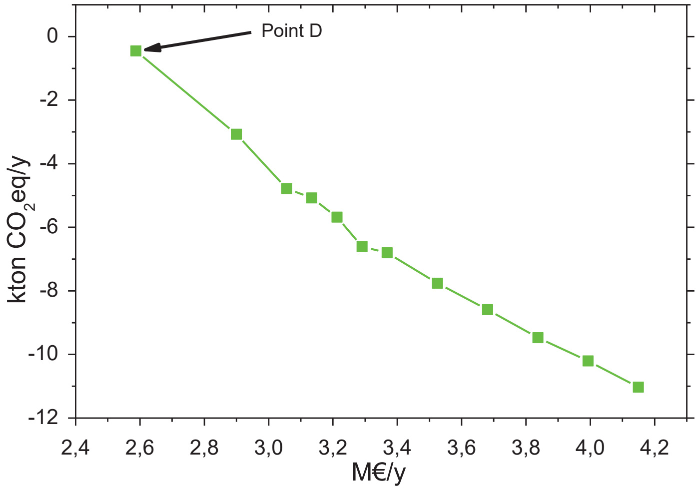

Figure 7. Pareto curve for scenario 2.

Table 4. Scenario 2: optimal emissions solution (point D).

Building	ICE [kW]	MGT [kW]	BOI [kW]	ABS [kW]	HP [kW]	CC [kW]	PV $[m^2]$	ST $[m^2]$	HST [kWh]	CST [kWh]
1	140	0	105	0	0	1	0	11	1579	826
2	840	0	0	420	0	0	0	0	4000	805
3	0	0	0	0	0	0	0	53	180	335
4	50	0	0	0	0	0	0	0	523	0
5	0	0	57	0	70	6	0	14	58	1200
6	0	0	62	0	0	0	0	13	58	1028
7	1200	0	0	525	630	15	0	0	4000	3007
8	0	0	10	0	70	0	0	0	0	0
9	280	0	0	0	0	0	0	0	1802	0

5.3. Scenario 3: grid-isolated

In the same direction of reducing CO$_2$eq emissions and primary energy consumption, another plausible scenario would be a completely isolated EC from the national electric grid. In this scenario, it was evaluated also the operation with natural gas or biomethane. The results demonstrated that a grid-isolated EC is not attractive from the economic and environmental viewpoints, either for natural gas or biomethane, which is in agreement, for instance, with references [23,24].

For the natural gas case, the optimal economic solution for an off-grid EC was 9.3% higher when compared to the optimal economic solution for grid-connected EC (point A, Fig. 6), which represents 212 k€/y. When the optimal CO$_2$eq emissions solution is analysed, the increase is even higher. The correspondent off-grid solution emits 21.2% more CO$_2$eq if compared to the equivalent solution for grid-connected (scenario 1). Besides, for this exact same comparison, the off-grid solution costs 2.2 times more.

In the case of biomethane, as expected, the emissions resulted zero. This is because the biomethane was considered net-zero CO$_2$eq emitter and there is no electricity bought from the main grid. When compared to the equivalent grid-connected solution (point D, Fig. 7), the grid-isolated one held a slight increase of 0.4% (which represents 12.6 k€/y) in the total annual costs. However, the grid-connected solution allows a CO$_2$eq compensation of almost 460 ton of CO$_2$eq/y. Moreover, considering the grid-connected (scenario 2), it could be possible to increase the CO$_2$eq compensation by around nine times by increasing the total annual costs by only 18%.

5.4. Brief comparison to carbon market and payback evaluation

As introduced in section 1, one of the foreseen directives from the “Fit for 55” package of the EU regards an update to the EU emissions trading system (ETS). According to the European Commission [25], international carbon markets have the potential to serve as a crucial factor in the cost-effective reduction of worldwide GHG emissions. This is demonstrated by the rising of emissions trading systems globally. In addition to the EU ETS, various national and sub-national emissions trading systems are currently in operation or being developed in several countries including Canada, China, Japan, New Zealand, South Korea, Switzerland, and the United States.

With lower environmental impacts and higher energy efficiencies, ECs have a substantial cost advantage if inserted in a carbon trading ecosystem [26]. Moreover, a personal carbon trading (PCT) scheme has been discussed in literature [27,28], as a promising and innovative policy tool to mitigate carbon emissions at the household and individual level, and to encourage the adoption of low-carbon lifestyles. In this sense, the present work analysed the cost of CO$_2$eq emissions reduction based on the data from Fig. 6. The reference cost was the one resulted from the optimal economic solution for scenario 1 (point A).

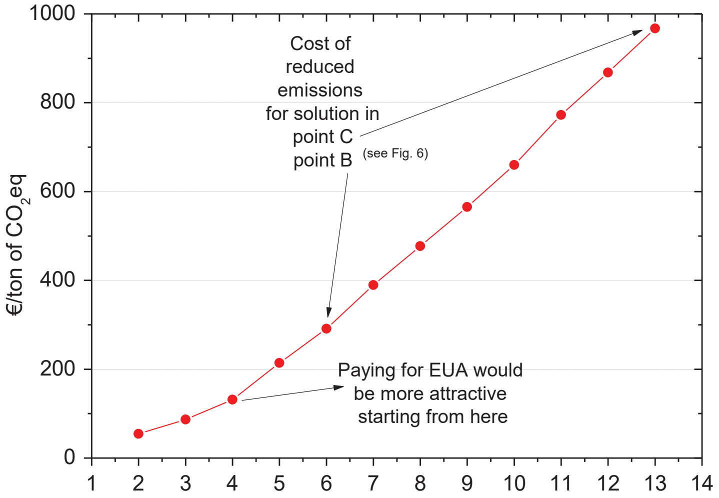

Figure 8. Cost of reduced CO$_2$eq emissions for each solution in the Pareto curve of scenario 1. Solutions 2 to 13 (see Fig. 6) are confronted to solution 1 (or point A) in order to compare results with the carbon market.

Figure 8 shows the cost of reducing CO$_2$eq emissions from solution number 1 (point A, Fig. 6) to each one of the other 12 solutions in the Pareto curve of scenario 1. Such cost raises from 54 (solution 2) to almost 970 €/ton of CO$_2$eq (solution 13). Considering an average European Emission Allowance (EUA) of 85 €/ton of CO$_2$eq [29] for the past year, the data suggests that, starting from the point indicated in Fig. 8, it would be economically more attractive to pay for the correspondent amount of EUA, rather than choose a solution for the EC with a lower CO_2eq emissions level. In order to have an idea, if solution in point B would be chosen over that of point A (Fig. 6), the cost increase would be around 560 k€/y. On the other hand, if point A is chosen and the correspondent EUA is paid, the cost increase would be around 163 k€/y. Note that all the solutions of the Pareto fronts depicted in Figs. 6 and 7 present both lower economic cost and lower greenhouse gas emissions than the conventional solution (CS) and, therefore all of them represent an improvement.

Table 5 presents the payback (PB), cost reduction (CR), and CO_2eq emissions reduction (CO_2R) for the four main solutions analysed in sections 5.1 and 5.2. All solutions were confronted with the CS scenario data. Although point C (optimal emissions solution) owns one of the highest CO_2R, its cost decrease was the lowest one, while its payback was the highest one. By comparing points A and B from the CO_2R point of view, the latter would be the best one. However, by joining the perspectives of PB, CR, and carbon market, point A solution would be more attractive since it would have lower PB and lower overall costs (including the payment of EUA). In the perspective of a gas grid fed 100% by biomethane, point D would be attractive if the goal would be to cut off and compensate CO_2eq emissions.

Table 5. Evaluated solutions, payback (PB), cost reduction (CR), and CO_2eq emissions reduction (CO_2R) with respect to the CS scenario.

Solutions (points)	PB (y)	CR (%)	CO_2R (%)
A	1.5	– 48	– 34
B	1.8	– 35	– 51
C	4.7	– 5	– 51
D	1.8	– 41	– 104

6. Conclusions

In order to cover new climate change concerned policies, such as the “Fit for 55” package from EU, and reach a low-carbon future, solutions should be presented throughout different sectors. This is the case, for example, of the efficiency of energy systems and buildings. For that reason, this paper assessed the performance of different scenarios for an EC, through a multi-objective optimisation approach. The EC comprises nine third sector buildings located in Pordenone, northeast of Italy, and was modelled through a mixed integer linear programming (MILP) model. The evaluated scenarios were: 1) Grid-connected - natural gas consumption, 2) Grid-connected - biomethane consumption, and 3) Grid-isolated.

The results have shown that, as expected, all three scenarios present better trade-off solutions when compared to the CS scenario (reference case), i.e., lower total annual costs and CO_2eq emissions. However, each one of the three scenarios presented its particularities.

For scenario 1, which represents the current scenario of natural gas consumption, the selected trade-off solution according to the Pareto curve (Fig. 6) was the one of point B. This solution holds a total annual cost 31.5% (or 1307 k€/y) lower when compared to the optimal CO_2eq emission solution (point C, Fig. 6), but with approximately the same emissions level. When compared to the optimal economic solution (point A, Fig. 6), the total annual cost of the solution in point B is 24.5% (or 560 k€/y) higher, while its total annual CO_2eq emissions is 26% (or 1923 ton of CO_2eq/y) lower. Nevertheless, if the carbon market is considered, and with the current price for each ton of CO_2eq (March 2023), the solution in point B would no longer be economically attractive. Instead, the solution from point A along with the correspondent EUA payment would result an economic saving of around 70% with respect to the solution in point B. Besides, point A solution owns the lower payback among the analysed solutions.

Scenario 2 represents the limit case of a natural gas grid in which its methane content is completely replaced by biomethane (which was assumed a net-zero emitter for this work). When comparing the optimal economic solutions between scenarios 1 and 2, one can see that an increase of 13.4% in the total annual costs (or 306 k€/y) could allow a reduction of 106% in the total annual CO_2eq emissions, i.e., emissions would be cut off and, besides, a CO_2eq compensation of 460 ton per year would be obtained. Therefore, considering the possibility of moving from the optimal economic solution in scenario 1 (point A) to the optimal economic solution in scenario 2 (point D, Fig. 7), the cost per ton of reduced CO_2eq emissions would be economically more attractive when compared to the carbon market.

The third analysed scenario is the one where the EC (in both scenarios 1 and 2) would be completely isolated from the national electric grid. Results demonstrated that the off-grid EC version is not attractive from economic or emissions viewpoints. In scenario 1, the total annual cost and CO_2eq emissions of the EC would be, respectively, 9.3% and 21.2% higher. In scenario 2 the cost increase would be only 0.4%, however, the EC would not be able to compensate CO_2eq emissions by selling electricity to the grid.

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Therefore, based on the obtained results, the implementation of an EC as the one analysed in this work would help not only to cope with new climate change policies (such as "Fit for 55"), but would be also economically more attractive than the current scenario.

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