Micro energy communities: collective residential heating system retrofits for CO₂ emissions abatement

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Abstract

Energetic renovations aiding the decarbonisation of the (residential) building sector are expensive operations. Micro Energy Communities (MECs) created by collective renovations are able to lower this barrier by decreasing the cost per household. This work focuses on the thermal system of a Belgian MEC, more specifically, this paper answers the question which collective heating system retrofit is able to lower the CO₂ emissions of the MEC at the lowest cost. A novel, graphical representation is developed and answers this question by showing the CO₂ emissions reduction, facilitated by a renovation, together with its Total Cost of Ownership (TCO). Several collective heating system retrofits are simulated using white-box models and their results demonstrate the value of the tool to select the preferred renovation based on either a cost budget or a CO₂ emissions abatement ambition. The graph assists in this selection process, as such accelerating the roll-out of collective solutions.

Highlights

• The installation of solar thermal collectors is the cheapest collective renovation strategy, but only for a limited amount of CO₂ emissions abatement.
• An appropriate (pricing) framework to valorise excess photovoltaic electricity shows to have a major impact on the decarbonisation potential of collective retrofits.
• Reaching the 2050 emission reduction targets is nearly impossible for the average residential building in Belgium, if no improvements in building envelope quality are carried out.
• Space cooling provision has a major impact on the cost difference between a GSHP and an ASHP based heating system.

Introduction

In order to meet the climate goals set by the Paris Agreement and the European Union, decarbonising the (residential) building sector is absolutely required (European Commission (2020), United Nations Framework Convention on Climate Change (2015)). Energetic renovations, such as improving the building envelope quality or replacing the energy systems, allow to reduce the building’s primary energy use and its dependency on fossil fuels. However, the building stock is slow to evolve as these renovations come at a high cost, which is a detrimental barrier. Therefore, cost-effective solutions need to be found. Collective energetic renovations are an appealing solution to decrease this barrier, as these allow for shared investments and lower the investment (and potentially also operation) costs per household (Meessens (2022)). By performing this collective renovation, a MEC can be formed. This paper focuses on a collective heating system for Belgian buildings and investigates which collective heating system retrofit is able to reach a pre-set CO₂ emissions reduction target at the lowest cost. In order to do so, a novel, graphical decision-making tool was developed. This tool maps CO₂ emissions abatement to costs and shows the CO₂ emissions reduction that a collective renovation can obtain compared to a benchmark system. Multiple collective heating systems can be mapped on the same graph which allows to see difficult-to-predict relations in a visual way, and supports decision making taking both CO₂ emissions abatement and costs into account. This graph could help to lower the barriers for carrying out energetic renovations and deploying MECs.

Base case

In this work, the MEC includes three neighbouring buildings for which several collective heating systems are compared to a typical Belgian individual heating system. Such a common Belgian heating system consists of a central heating system with a condensing gas boiler that provides space heating and domestic hot water (DHW) (Ipsos (2019)). Cooling is not yet present in this base case. However, the collectively renovated heating systems will include cooling as its importance will definitely increase due to climate change (Ipsos (2019)). Moreover, two types of heat emission systems (radiator and floor heating) are considered.

The next section discusses the applied methods and elaborates on the heating and cooling system component selection, the cooling provision, a qualitative discussion on the proposed graphical decision-making tool and the modelling approach. The Results section presents the results of the selected collective heating systems, represented in the novel graphical tool, and discusses the collective systems with their CO₂ emissions and TCO trajectories. Said differently, this section will present the decision-making
graph applied to the analysed MECs to see which energetic renovation can realise the highest CO₂ emissions reductions at which costs. The final section presents the conclusion and summarises the key innovations.

Methods
This section discusses the applied methods and starts with the criteria, the three C’s, that form the basis for decision-making throughout this work. This is followed by a study on which components can be used for the renovations and what collective layouts they can form. Thereafter, a part is dedicated to the cooling provision, but the main focus is on the decision-making tool and how the graph is constructed and should be interpreted. The final part of this section discusses the simulation environment and the demand profiles that were used, as all collective heating systems presented on the graph have been obtained via simulations.

The three C’s
To be able to size the retrofits and construct a basis for the control strategy of the simulations, the three C’s are introduced. The three C’s represent three prioritised criteria:

1. Always provide thermal comfort
2. Lower the CO₂ emissions as much as possible
3. Lower the costs as much as possible

Based on these criteria, the production units are sized with respect to the peak demand. In the rule-based control strategy, that was developed for the dynamic simulations, this leads to always using the most green production unit first, storing thermal energy when electricity prices will be higher in the near future and providing thermal comfort in any case.

Component selection
Before a collective retrofit can be performed, it should be made clear which components make up a retrofit. The condensing gas boiler, defined by the base case heating system, is present in each collective layout as it can be preserved for two reasons:

• The formation of a hybrid system in which the existing condensing gas boiler can provide peak demand on very cold days
• To create a more circular approach

In addition, a literature study was performed with the intention of selecting a few components that suit the scale of three residential buildings and are not too site-specific. The components that were withheld from this study are:

• Solar thermal collectors (STC); these collectors generate heat from solar irradiation and can reach the temperature range used in DHW applications for which they are ideal in the residential context (Sid-dharth et al. (2015)).
• Air source heat pump (ASHP); this component upgrades heat extracted from surrounding air and is known as a crucial component to aid the decarbonisation of buildings (European commision (2020)).
• Ground source heat pump (GSHP); this component upgrades heat extracted from the ground, thus requiring ground heat exchangers, turning it more expensive. The higher cost is compensated by a higher seasonal coefficient of performance (SCOP) and the possibility to use passive cooling, i.e., cooling without a heat pump (Aprianti et al. (2014)).
• Storage tank; a simple water tank that enables sensible (short-term) thermal energy storage on residential scale (Basecq et al. (2013)).
• Borehole thermal energy storage (BTES); storage of thermal energy in the underground via injection of heat in open or closed systems (Mangold and Deschaintre (2015)).
• Photovoltaic (PV) panels; these panels generate electricity from solar irradiation. When combined with heat pumps, green heat can be produced very efficiently (SolarPower Europe (2023)).

Combining these five components, and the condensing gas boiler, leads to a long-list of 31 different collective heating system layouts. Some of these layouts are, however, not interesting to reduce CO₂ emissions which enables to shorten the long-list. The exclusion of some layouts is based on the three C’s and domain knowledge. For example, adding a storage tank to the base case heating system, does not allow to lower the emissions while it does increase the cost, meaning that it is conflicting with the criteria (Meessens (2022)). 11 remaining retrofits make up the shortlist and are modelled and simulated (next to the benchmark base case as described in the introduction).

Space cooling methods
Based on the different components for heating and the emission side, the space cooling provision varies over the shortlisted layouts. When radiators are present, cooling has to be provided by air-air heat pumps which directly cool the air in the rooms, whereas a floor system allows for cooling via the main heat emission system. When a GSHP is combined with a floor system, passive cooling can be used which is significantly cheaper and reduces more emissions compared to the air-air heat pumps. When an ASHP is combined with a floor system, a four-pipe heat pump, that allows both heating and cooling at the same time, will be used which is cheaper than the combination of a two-pipe heat pump and air-air heat pumps.
Cost - CO₂ abatement graph

A novel, graphical representation was developed to aid the selection of collective heating system retrofits that target a pre-set CO₂ emissions reduction at the lowest cost. This method is not only applicable to collective heating systems as it can easily be extended to a single household, entire neighbourhoods, office buildings, renovations including building envelope quality improvement as well, etc. provided the additional simulations are made. Figure 1 shows a simplified version of the actual graph to conceptualise the idea more clearly. The horizontal axis of this graph represents the reduction in CO₂ emissions a collective layout can achieve compared to a base case system. Consequently, the base case is on the vertical axis with no CO₂ emissions reduction. The other extreme is the green vertical line on the right-hand side which represents zero CO₂ emissions. In addition, the graph shows the emission reduction targets for households by 2030 and 2050 (2.4 and 0.53 tonnes of CO₂ per year respectively (Vlaamse overheid (2019))), which puts the results into perspective and allows to select the cheapest heating system layout able to achieve these targets. The vertical axis represents the net present value of the TCO (capital, operational, maintenance and installation costs) for the heating system over a 30-year period. This time horizon is needed to correctly compare renovations based on the capital and operational expenses and was chosen in accordance with the expected lifetimes of the components and to reach the year 2050 which is a very important milestone set by multiple environmental targets. A net discount rate of 2.2% was used throughout this work for the net present value calculations (Meessens (2022)).

Figure 1 also shows three red curves, each one representing one collective system layout. On the non-simplified graph, these curves are the result of dynamic simulations. Depending on the components that are present, the curves are constructed in a different way. When only STCs are present, the curve represents a parameter sweep of the collector area. This means that moving to the right on the curve equals increasing the area of STCs, causing more energy, previously generated by gas, to be replaced by renewable energy and hence reducing the CO₂ emissions. Placing extra collectors does come with an extra cost, thus moving to the right on this curve also means moving up. The rightmost point corresponds to the roof of the houses being completely covered with STCs reaching the maximal CO₂ emissions abatement possible for this retrofit. When a heat pump is used (without any STC or PV), the curve is a parameter sweep of the heat pump load duration. This means that moving to the right on this curve equals a higher heat pump load duration, hence more of the thermal energy will be delivered by the heat pump. Considering that the electricity price is much higher than the price for gas (at the time of writing (Elexys (2022))) moving to the right (reducing the CO₂ emissions) means an increasing cost. The rightmost point on this curve corresponds to the heat pump delivering as much thermal energy as possible. Note that this point does not guarantee zero gas usage as the temperature regimes at which the heat should be delivered can be higher than the heat pump can provide, causing the gas boiler to be required to guarantee thermal comfort. This curve will not be a linear curve on the actual graph due to the dynamic electricity price that is considered.

The third possible combination that characterises how a curve is constructed is the combination of a heat pump and STC or PV. Installing PV panels comes with a cost, however, they also allow to reduce the CO₂ emissions by feeding a heat pump. The larger the PV area, the higher the CO₂ abatement and cost. The heat pump can also be used in exactly the same way as was explained before. Therefore, the only difference for this type of retrofit is that the method now combines both previous methods. Hence, this curve is essentially a combined parameter sweep of the STC and/or PV area and the heat pump load duration. The curve is finally constructed by always applying the next cheapest option (the three C’s) to reduce a same amount of CO₂, be it installing extra square meters of panels/collectors, be it increasing the heat pump load duration.

Simulation environment and demand profiles

The Modelica modelling language was used to build the models and Dymola (Dassault Systèmes (2022)) has served as the dynamic simulation environment. Modelica is object-oriented allowing for a very convenient modular approach and uses multi-physics modelling. The three libraries used are: IDEAS (Jorissen et al. (2018)), Modelica Buildings library (Wetter et al. (2014)) and Modelica StateGraph2 (Olsson (2022)) libraries. IDEAS and Modelica Buildings library hold many components with regards to building elements and HVAC components. Modelica StateGraph2 provides components to model discrete events and was used for the rule-based control strategy.

As was previously mentioned, the focus in this work is on the production side of the heating system. Therefore, the demand side of the MEC has been simplified (not using any dynamic model) and is represented by fixed demand profiles. In this work, average Belgian demand profiles have been constructed. These profiles include average occupant behaviour, an average building envelope, average internal gains, etc., and hence represent an average Belgian case. Although it could be argued that the demand side should be modelled dynamically to have more reliable results, a relative assessment of the retrofits with
fixed profiles is relevant, as all retrofit scenarios will use the same demand profiles. Because fixed demand profiles are used, thermal comfort is satisfied when the energy system can fulfil the imposed demand profile.

Three different profiles, one for space heating, one for space cooling and one for Domestic Hot Water (DHW), were constructed. For this, a two-step approach was followed: (i) find a suitable trajectory of the profile, and (ii) normalise and scale the trajectory to a profile for which the yearly values correspond to the Belgian averages. For the first step, a general and suitable profile was searched in literature. Figure 2 shows the profile that was used to model daily variations in the space heating demand and Figure 3 shows the profile that was used to model yearly variations in the space heating demand. Combining both delivers a general profile suitable for residential buildings with daily and yearly dynamics. In a second step, this general profile is normalised and scaled to, in this case, Belgian averages. In this way, profiles for heating, cooling and DHW were constructed that represent Belgian average data starting from a realistic profile. Figure 4 shows the resulting demand profile for space heating on a two-day basis, indicating the daily variations. The Belgian averages that were used for scaling equal 17 MWh for heating (Peeters (2021)), 1.4 MWh for cooling (Persson and Werner (2015)) and 3 MWh for DHW (Vitens (2022)). Finally, a Belgian typical meteorological year (TMY) weather data file has been used to set the boundary conditions for the energy technology models (Filip Jorisissen (2023)).

Results

Three cost - CO\textsubscript{2} abatement graphs are shown: one for all layouts with radiators and without valorisation of excess PV electricity, Figure 5, one for all layouts with floor emission systems and again without valorisation of excess PV electricity, Figure 6, and a third one for all layouts with floor emission systems and valorisation of excess PV electricity at 30% of its retail price, Figure 7. In all three figures, the dashed lines represent the retrofits that contain an ASHP, the full lines represent the retrofits that contain a GSHP and the dotted-dashed line represents the renovation containing only solar thermal collectors (STC) and a storage tank (in orange) or the retrofit in which each component is present (light blue). The remaining colour codes are explained in the legend of the graph. In this legend it can also be seen that every layout contains ‘gas’ as every retrofit starts from the base case heating system and preserves the condensing gas boiler.

The effect of the emission side

Figures 5 and 6 show that the STC retrofit is the cheapest, but it only enables a minor reduction in CO\textsubscript{2} emissions. A parabolic shape can be observed because the gas usage decreases with increasing STC area. This is caused by saturation of the STC potential. Hence, the CO\textsubscript{2} emissions abated per square meter decreases while the cost increases causing this parabolic shape. This phenomenon is very important as it is observed for PV panels as well and therefore will appear in a lot of curves. Another interesting point is that this curve is monotonously increasing on Figure 5 whereas it shows a minimum on Figure 6. This is caused by the higher temperature regimes present in radiator systems. Moreover, the avoided cost by installing a small number of STCs (when floor emission systems are used) is larger than the increase in investment cost. A last point about this curve is that the total CO\textsubscript{2} emissions abatement that can be achieved by a floor emission system is greater than the abatement for the radiator system. This is again due to the higher temperature regimes needed in radiator systems. Moreover, the STC retrofit starts from the base case heating system and therefore it can also be seen that every layout contains ‘gas’ as every retrofit starts from the base case heating system and preserves the condensing gas boiler.

Curves containing a heat pump also exhibit a parabolic behaviour, although due to another effect. Because of the use of a dynamic electricity price and the three C’s, a heat pump will be used first at the moments the electricity price is the lowest. Therefore, when gradually increasing the heat pump load duration, the heat pump will be active at more expensive moments causing the unit price for CO\textsubscript{2} emissions reduction to increase, which leads to a parabolic shape.

A second observation in Figure 5 is that all retrofits barely make the 2030 standard. However, if Figure 6 is investigated, every retrofit - apart from the STC one - reaches the 2030 standard while none of them reaches the 2050 standard. This clearly shows that an all radiator system is harder to decarbonise which is due to multiple
Figure 5: Cost - CO₂ abatement graph if radiators are used, no valorisation of excess PV electricity

reasons:

1. Cooling cannot be provided via passive cooling (typically done when a GSHP is present);
2. The SCOP of the heat pumps will be lower due to the higher temperature regimes;
3. Lower efficiency for the STCs, again due to the higher temperature regimes;
4. Higher storage tank thermal losses.

It can also be observed that all solid lines intersect the vertical axis above the dashed lines, which indicates that the investment costs for GSHP retrofits are higher than for the ASHP retrofits. The cost difference between the ASHP and GSHP is however significantly different in both graphs which is due to the way cooling is provided. As was already mentioned, when radiators are present, cooling has to be provided by directly cooling the air in the rooms, whereas a floor system allows cooling via the heat pumps. Passive cooling can be applied when a GSHP is present (using its connected borefield) and is significantly cheaper than air-air heat pumps as the latter comes with an extra investment cost to provide cooling. The difference is less pronounced when an ASHP is present as the difference between a heat pump that allows both heating and cooling at the same time (needed according to the three C’s) and the combination of a standard heat pump and air-air heat pumps is smaller.

Furthermore, the shape of some curves immediately captures the eye due to their almost step-wise evolution. Such a step-wise curve is only observed when a heat pump and either STCs or PV panels are present as a consequence of the way the double parameter sweep is performed. As was explained, the curves are constructed by always applying the next cheapest option to reduce the same amount of CO₂ emissions which causes this behaviour. For example, if increasing the heat pump load duration has a lower cost per unit CO₂ emissions abatement than adding extra STCs or PV panels, then the heat pump load duration will be increased in the next simulation step.

Returning to the research question of this work, which retrofit is able to lower the CO₂ emissions at the lowest cost, it is becoming clear that this depends on the ambition set. For both emission systems (radiators and floor heating), the cheapest retrofit is installing STCs. If the three households want to reduce their emissions further, placing an ASHP is the way forward for both emission systems. However, if the 2030 standard is the goal and only floor emission systems are present, an ASHP alone is sufficient. In case of an all radiator system, PV panels are needed as well. Reducing the emissions further means that a retrofit needs a GSHP with additional STCs for a radiator system. This retrofit, a GSHP and STCs combined with a storage tank, is also the retrofit able to reduce the emissions the furthest when radiators are considered. To reduce the emissions further when floor emission systems are present, PV panels accompany the GSHP, but the retrofit able to reduce the emissions the furthest is the same as for the radiator emission system. This proves the value of this graph as it can effectively be used as a selection tool in designing a collective heating system based on a CO₂ emissions reduction target.

It can be argued that the limited potential in reaching the emission standards is due to the used demand profiles, as the average household does correspond to a rather high energy demand; an EPC value of around 372 kWh/m² (Vlaamse overheid (2023)). For comparison, the Belgian goal towards 2050 equals 100 kWh/m² meaning that a lot of renovation work lies ahead while the building park only slowly evolves.
Effect of the excess photovoltaic electricity

Figures 5 and 6 consider no valorisation of excess photovoltaic electricity. However, when there is no heating or cooling demand and the storage tank is fully charged, newly produced electricity from the PV panels cannot be used in the local system. In the previous analysis, this electricity was not used nor injected into the electricity grid, and this might have had a significant impact on the results. Therefore, the analysis is extended to investigate the effect of valorising the excess electricity at 30% of the electricity retail price. Electricity generated by PV has no embedded CO\textsubscript{2} emissions (taking only operational CO\textsubscript{2} emissions into account) and therefore avoids the generation of an amount of CO\textsubscript{2} equal to the carbon intensity of the grid. Put differently, when PV electricity is injected in the grid, an amount of CO\textsubscript{2} equal to the carbon intensity of the grid is avoided as PV electricity has zero emissions. Figure 7 shows the graph for this situation where the excess PV electricity is injected in the grid.

The first thing that stands out is that the 2050 standard can be reached. Using the excess PV electricity in essence stretches each curve (containing PV panels) to the right as the full PV potential is now used, which reduces the emissions further. It is thus key to value the excess electricity appropriately to reach the 2050 standard. In addition, the preferred retrofits change: the retrofit containing a GSHP and PV panels is now the preferred one to reduce the CO\textsubscript{2} emissions from the moment it becomes the cheapest option. This clearly indicates the value of PV panels towards the future, providing that exchange with the broader energy system is possible, and thereby implementing a proper valorisation strategy.

Conclusion

This paper answers the question which collective heating system retrofit has the lowest cost to reduce CO\textsubscript{2} emissions, in particular for a micro energy community of three residential buildings. The answer to this question depends on how much CO\textsubscript{2} has to be abated. For a minor amount, solar thermal collectors are clearly the winners regardless of the heat emission system used. However, if the goal is to reach the 2030 emission standard, the cheapest option is to install an air source heat pump and photovoltaic panels when only radiators are present. If only floor emission systems are present, installing an air source heat pump is the cheapest option. The conclusion is that the retrofit containing a ground source heat pump and solar thermal collectors can abate most CO\textsubscript{2} emissions for both emission systems investigated. The 2050 standard can only be reached if the excess electricity from the photovoltaic panels is valorised. This also signifies the importance of how surplus renewable electricity is managed.

The strength of the novel graph developed is the simplicity with which complex conclusions can be presented and its great applicability. It is not only suitable for a case of three households, but can also be applied to a case of one household, entire neighbourhoods, office buildings, renovations that include insulation works, etc. In addition, this graph can effectively be used as a practical renovation tool. Take, for example, three households that want to collectively renovate their heating system. They can use the tool to select the energy system that will reduce the most CO\textsubscript{2} emissions for a pre-defined budget, or to select the cheapest energy system for a pre-defined CO\textsubscript{2} emissions reduction target (e.g. 2050 emission standard). The developed graphical representation proves to be an effective decision-making tool, able to lower the barrier for energetic renovations and can as such accelerate the roll-out
of collective solutions.

**Future work**

It was argued before that the demand profiles represent buildings with a rather high energy demand. Eventually, the 2050 target could have been reached more easily, maybe even with an ASHP only, if demand profiles of low-energy buildings were used. Hence, it might be interesting to assess the influence of different demand profiles. However, to avoid the discussion on the demand profiles entirely, dynamic modelling could be used to represent the demand side. This allows for more flexibility on the demand side and poses the correct definition of thermal comfort. Subsequently, the dynamic models of the demand side allow for including the building envelope and the emission system as part of the retrofits. This extension leads to a more holistic order (building envelope - emission system - heating/cooling system) in the decarbonisation process of the residential building stock. The graph could also inspire policymakers in setting priorities for subsidies: the retrofit that is able to reduce the emissions the furthest might be the most interesting one to subsidise.

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