POTENTIAL MACRO-ECONOMIC BENEFITS OF OPTIMIZING BUILDING RENOVATION ROADMAPS TOWARDS 2050 ON A CITY SCALE: A BELGIAN CASE STUDY.

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Abstract

In this study, the Urban Energy Pathfinder (UEP) is used to evaluate the potential savings that can be obtained by scaling up energy and/or CO_2 emission targets from the individual building level to the district or city level. Combining building energy simulation models with district level data, the UEP estimates the investment and operational costs needed to reach specific renovation goals. The software also computes energy and GHG emission savings, the total cost of ownership for an elaborate selection of building renovation measures and district heating solutions. This paper investigates a case study of three representative districts in Flanders. Results demonstrate that depending on the CO_2 targets imposed on the district, total cost of ownership reductions of up to 65% can be obtained by prioritizing target buildings and measures rather than following a uniform renovation strategy.

Introduction

The EU long-term renovation strategy aims towards a highly-efficient and decarbonized building stock by 2050. This ambition request a cost-effective transformation of existing buildings into nearly zero-energy buildings. With the so-called Renovation Wave as one of the Green Deal flagships (European Commission, 2020), the EU makes urgent renovation of our buildings and infrastructure a priority, not only to combat climate change, but also to alleviate energy poverty for millions of Europeans and to ensure that buildings provide a comfortable, healthy and affordable living and working environment (Raph, 2020).

While past and current energy saving policies often translate to minimal - yet uniform - renovation requirements for all buildings, multiple studies have demonstrated that the impact and cost-effectiveness of renovations are strongly case dependent (Lambie, 2020, Lizana, 2016, Sun, 2017). In this study, potential system cost reductions are identified that may be obtained when moving energy and/or CO_2 emission targets from the individual building level to the district or city level.

Methodology

The Urban Energy Pathfinder

The Urban Energy Pathfinder (UEP) is a web-based multi-layer decision support tool for regions and cities who want to take a proactive role in the development of their energy transition strategies. The UEP provides a holistic energy plan by calculating energy, CO_2 emissions, and financial conditions for renovation scenarios and energy technology measures at building, district and city level. The scenarios include a mix of technological measures such as district heating/cooling networks, building renovation measures and decentralized renewable energy production technologies.

For the demand side, the UEP follows a bottom-up modelling approach in which the energy use of individual buildings - including energy use for space heating, domestic hot water production and electricity use for lighting and plug loads - are modelled based on the EN520026 series using the EnergyVille Building Energy Calculation Service (EBECS). Monthly building energy simulations are used to quantify the energy use for the current district situation as well as the impact of different renovation measures. Building geometry, thermal properties of the envelope, HVAC system characteristics and user-behaviour characteristics are specified on individual building level using an extensive data model.

The data model combines bottom-up data – e.g. LOD2 for building geometry derived from LiDaR data (VITO, 2020), open GIS data on building function (geopunt.be), open street-level data on gas and electricity consumption (Fluvius, 2018) - with top-down data - e.g. district-level data on construction year and household composition (Census 2011), correlations between construction year and envelope characteristics…- to complete all necessary model parameters.

As a tool, the UEP also provides the option to further detail and specify model parameters down to individual building level. To fill the district's heating demand using renewable energy, the UEP allows to evaluate both solutions on building level (e.g. air-to-water or ground-water heat pumps) as well as collective solutions based on district heating (e.g. based on industrial waste heat). In this work, only individual solutions shall be investigated.

As an output of the UEP energy simulations, the energy uses per energy carrier (gas, oil, electricity, heat) are obtained for each building in the neighbourhood and this for all technically possible combinations of the selected renovation and heating measures. Based on these energy use results, the corresponding CO_2 emissions and energy costs are calculated. The latter are compared against the corresponding investment costs in the economic model to compute the total cost of ownership (TCO) and CO_2 abatement costs for all possible district renovation and heating scenarios. In this study, the TCO is calculated in its simplest form as:

$$TCO = I_0 + \sum_{i}^{n} \frac{C_{E,i}}{(1+d)^i}$$

With I_0 the total investment cost for the scenario in year 0, $C_{E,i}$ the energy cost for year i, d the discount rate and n the lifespan. For this study we assume n = 30 for all technologies.

The CO_2 abatement cost, interpreted as the cost of reducing on ton of CO_2 emissions, is calculated as:

$$Ab.Cost_{CO_2} = \frac{TCO_{scen} - TCO_{ref}}{\sum_i^n (CO2_{ref,i} - CO2_{scen,i})}$$

With, TCO_{scen} and TCO_{ref} respectively the total cost of ownership in euro of the analysed scenario and that of the reference scenario. $CO2_{x,i}$ is the annual CO_2 emissions in ton in year i.

Note that for the CO_2 emissions in this study we differentiate between ETS and non-ETS emissions. Thereby, electricity falls under emission trading scheme (ETS) for which CO2 emissions are capped. As such, under ETS regulation one can argue that when a gas or oil boiler is replaced by a heat pump, the CO_2 emissions related to the electricity use of this heat pump are 0. However, not considering the macro effects of a massive shift electrification of the heat demand may lead to perverse effects regarding the need for energy savings in the building sector. Therefore, in this paper we compare two situations:

1) Electricity use is not included in the CO_2 emissions (non-ETS emissions only)
2) Electricity use gives rise to CO_2 emission with a constant CO_2 intensity equal to today's EU average.

Finally, a pareto optimization module has been implemented which searches the pareto optimal combination of renovation measures and district heating solutions to reach a certain level of energy savings or CO_2 emission savings. As a cost function, the UEP can use the total investment cost or the TCO. Taking a societal perspective, this paper analyses the CO_2 emission savings using the TCO as cost function. Hence, the pareto optimal solution is the optimal set of renovation measures applied to optimal set of buildings in order to reach a certain CO_2 emission target at the lowest TCO.

Case study

In this paper, the simulations are conducted on 3 typical residential districts as encountered in Flanders. Each district consists of a circular area of 5 hectares (126,16 m radius) around a central coordinate.

The 3 districts, shown in Figure 1, represent 3 types of urban environment relevant for Flanders:

1. Central urban;
2. Peri-urban;
3. Suburban.

Building geometries for these districts are obtained from a LOD2 GIS model derived from Lidar images gathered in the period 2013-2015 (VITO, 2020). From the LOD2 model, the building volume, roof area, floor area and external wall areas (aggregated along the 4 cardinal directions) are obtained. A window-to-wall ratio (WWR) is used to specify window areas for each orientation. The WWR ratio and the thermal envelope properties (U-values) are sampled from a stochastic model trained on the Flemish EPC database (De Jaeger, 2018). Figure 2 shows the distribution of total floor area, construction year and total heat loss coefficients for the 3 neighbourhoods. The total heat transfer coefficient in Figure 2 is calculated as the sum of the sum of the direct transmission heat transfer coefficient between the conditioned zone and the exterior ($H_{tr,e}$) and the heat transfer coefficient for ventilation (H_V):

$$H = H_{tr,e} + H_v$$

$$H_{tr,e} = \sum_i b_{tr,e} U_i A_i$$

$$H_v = c_a \rho_a V_{protected} (n_{inf} + n_{hyg})$$

with U_i, A_i and b_i respectively the U-value, total surface area and temperature factors for component *i*. $V_{protected}$ is the protected volume of the building and n_{inf} and n_{hyg} the air change rates due to respectively infiltration and hygienic ventilation.

In line with the national energy statistics, all buildings are assumed to be equipped with central heating, of which 70% are considered to be gas boilers. The remaining 30% are modelled as oil boilers with a total system efficiency of 54%. As the current penetration of mechanical ventilation systems in existing buildings is marginal in Belgium, no mechanical ventilation systems are included. In line with common practice, domestic hot water production is assumed to be centrally produced by the same boiler as space heating.

Figure 1 Selected representative districts (central coordinates in Belgian Lambert projection)

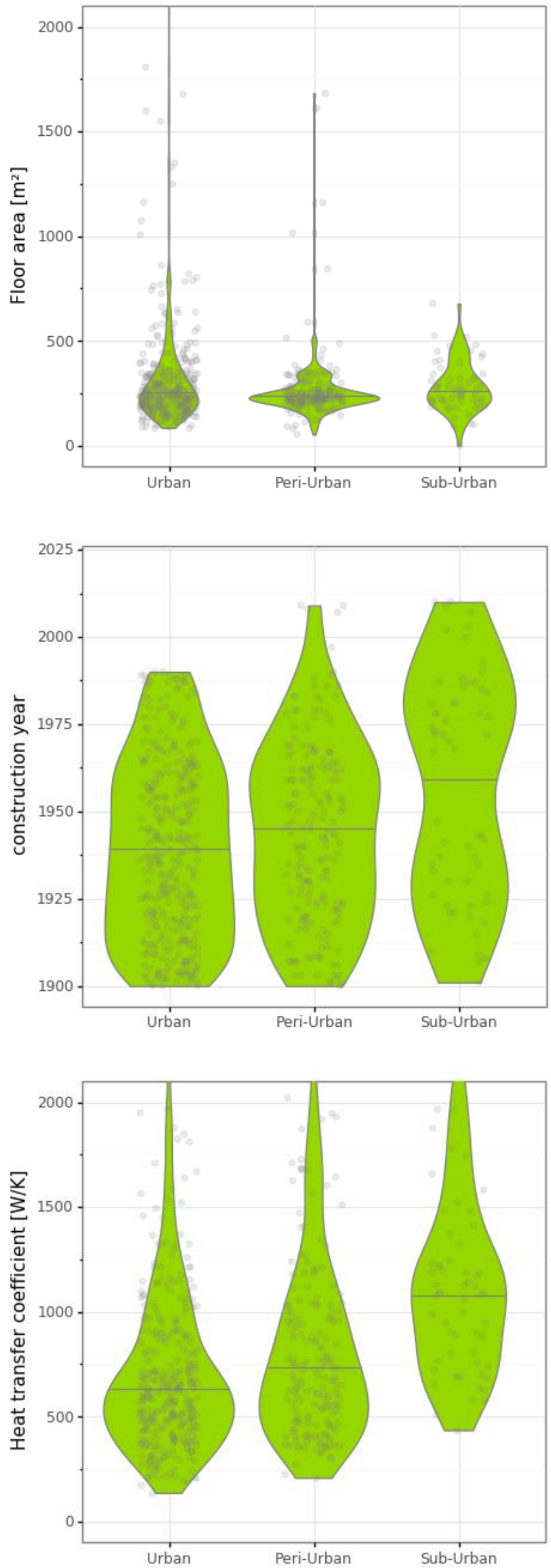

Figure 2 Distribution of floor area (top), construction year (middle) and heat transfer coefficient (bottom) for the 3 representative districts

Scenarios

In the UEP scenarios are split between building level renovations aimed at reducing the heat demand and heating scenarios aimed at providing the remaining heat demand in an efficient manner.

In terms of building level renovation, the following measures have been implemented:

- window replacement: insulated PVC window frame with triple glazing resulting in a window U-value of 1.2 W/m²K. (cost: 600 €/m²)
- exterior wall insulation: exterior wall insulation is placed with a plaster finishing layer until the U-value meets the target of 0.24 W/m²K (180 €/m²)
- cavity wall insulation: filling the open cavity with cellulose until the U-value meets the target of 0.6 W/m²K (30 €/m²)
- underfloor insulation: insulation applied to basement ceiling until the U-value meets the target of 0.24 W/m²K (30 €/m²)
- roof insulation: Sarkin roof is placed for pitched roof (cost 270€/m²) and extra insulation for flat roof (cost 100€/m²) until the U-value meets the target of 0.15 W/(m²K)

Technical constraints have been considered:

- cavity wall insulation: requires an empty or partially filled cavity wall. This is assumed to be the case for buildings constructed between 1960 and 1990 with a U-value for walls higher than 0.6 W/m²K.
- floor insulation: is only applied when a building has a basement as taking out the existing floor to apply slab on ground insulation was deemed to be techno-economically infeasible.
- cavity wall insulation and exterior wall insulation cannot be applied simultaneously.

Roof-mounted PV are also considered as possible renovation measure. While new tariff structures are being composed, at the moment, residential PV production is still compensated at consumer electricity tariff with a maximum equal to the annual cost of electricity demand. A typical 4 kWp household installation is modelled at 4.000 € for the panels, inverter, installation and taxes. The prosumer tax which is currently applicable in Flanders. is however excluded.

For the heating scenarios, three possible options have been investigated. The first continues on business as usual and replaces existing boilers by high-performant condensing gas boilers at 3500 € per dwelling. The second foresees air-to-water heat pumps for heat production with an SPF of 2.5 when coupled to radiator heating and 3.2 when coupled to underfloor heating. The investment cost for the heat pump is set at 8000 € per dwelling, assuming that the existing emission system can be reused at low temperature as a result of the combination with adequate envelope renovation measures. Therefore, the heat pump is assumed to be only viable when the heat demand is below 100 W/m².

Lastly, a scenario with district heating is explored. For simplicity we assume that in the district heating scenario 100% of buildings will connect to the heating network. The impact of lower connection rates is examined in the sensitivity analysis. Two variants of the district heating scenario have been implemented. A high temperature variant whereby district heating temperatures are adequately high to provide both space heating and domestic hot water directly, and a low temperature variant. In the low-temperature variant booster heat pumps with a fixed COP of 3 are used to increase the water temperature when needed for space heating. The investment cost for these booster heat pumps is estimated at 5000€ per building. Direct electrical resistor heating is used when the temperature increase is only needed for domestic hot water at an investment cost of 500 €.

Investment costs for the measures have been compiled from the official ABEX 2019 (ABEX, 2019) issue supplemented with data from (commercial) price offers, feasibility studies, reference projects and other price indications (Vandevyvere, 2019).

In order to limit the size and complexity of the figures only 4 possible district renovation scenarios are shown and compared against the current situation. These scenarios are:
- ‘**50%**’: the pareto optimal building retrofits that result in a 50% reduction of CO_2 emissions on district level.
- ‘**90%**’: the pareto optimal building retrofits that result in a 90% reduction of CO_2 emissions on district level.
- ‘**light**’: a uniform light retrofit package consisting of boiler replacement, exterior wall insulation and a PV system is installed in all buildings
- ‘**heavy**’: a uniform heavy retrofit package consisting of a heat pump, roof and wall insulation and a PV system is installed in all buildings.

Note that the composition of the light and heavy retrofit packages has been chosen based on the combination of renovation measures that – as a package – occurred most frequently in respectively the 50% and 90% scenarios.

For each of these renovation scenarios the district heating variants are shown in the results below. In those cases, the investments in individual heating systems in each of the packages has been replaced by investment in district heating under the assumptions described above.

Results

This section summarizes the main results from the analysis of scenarios. Taking a system perspective into building retrofit targets, total cost of ownership and CO_2 abatement costs are defined as the main KPIs in the present work. The energy use and energy costs, CO_2 emissions and investment costs are also shown as they give more detailed insights into the differences found in total cost of ownership and CO_2 abatement cost for the different scenarios.

Energy use and costs

Figure 3 shows the total energy use as the sum of electricity, gas and oil within each district. The figure shows that on average, the energy use decreases by 44% and 80% respectively for the '*50%*' and '*90%*' scenarios (hereafter referred as the "optimized" scenarios) with respect to the current situation. For the 'light' and 'heavy' scenarios ("uniform" scenarios) the average reduction in energy use are respectively 47% and 88%. The slightly lower average in energy savings observed for the optimized scenarios ($\bar{x}$=62) when compare to the fix package scenarios ($\bar{x}$=67.5) can be explained by their position on the pareto optimal. While some buildings with a low economic renovation potential undergo less intensive renovation measures, those with high renovation potential apply more strict measures.

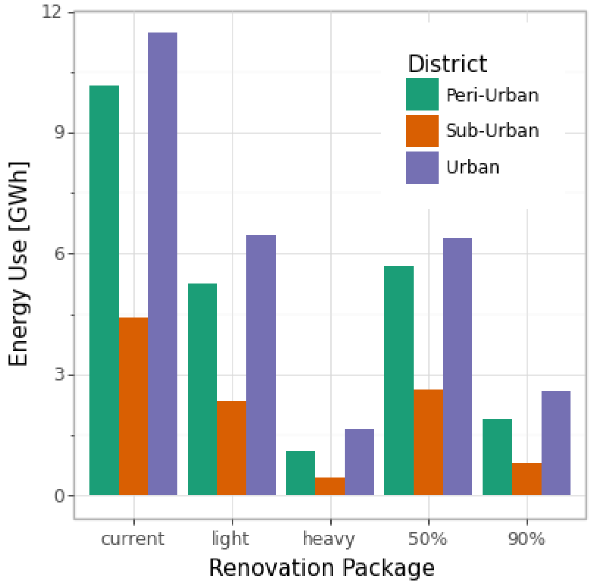

Figure 3 Total energy use as function of the renovation packages

It is also observed in Figure 3 that reaching respectively 50% and 90% CO_2 emissions savings does not require 50% and 90% energy savings. The latter is explained by the introduction of local PV production and the decision to take into account only ETS emissions.

The resulting energy costs are shown in Figure 4. Note that energy costs are lower for the light renovation scenario in the Urban district and for the 90% scenario in the Sub- and Peri-Urban districts. The energy costs hence do not decrease proportional to the energy savings because of the high price of electricity compared (0.27 €/kWh) to gas (0.06 €/kWh). This price difference is higher than the gains in efficiency when substituting a gas boiler by an air-to-water heat pump. Under the current prices the gas boiler is still the cheapest technology for heating. Evidently, as shown further, switching to more efficient natural gas boilers does not suffice to meet the long-term CO_2 targets.

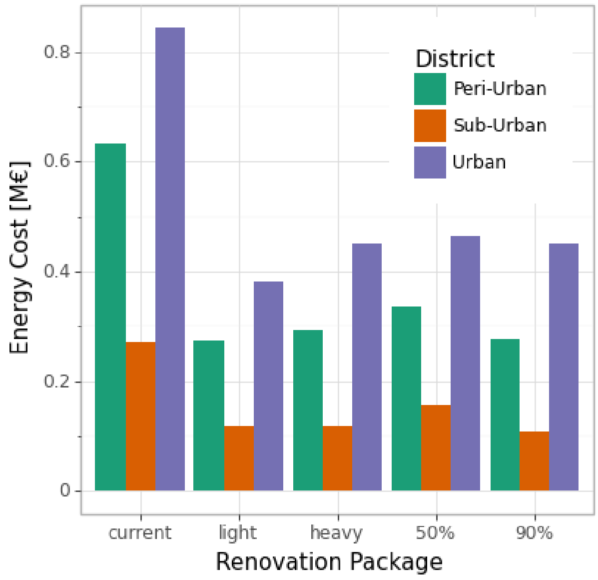

Figure 4 Total energy cost as function of the renovation packages

CO_2 emissions

Figure 5 shows the CO_2 emissions in each of the districts for the different retrofit scenarios. Under the assumption that only non-ETS emissions are included, the heavy renovation scenario in which all houses have switched to heat pumps is 100% decarbonized. For the light renovation scenario CO_2 emissions are on average 51% lower than for the current situation. For the optimized scenarios the targeted reduction of 50% and 90% have been reached.

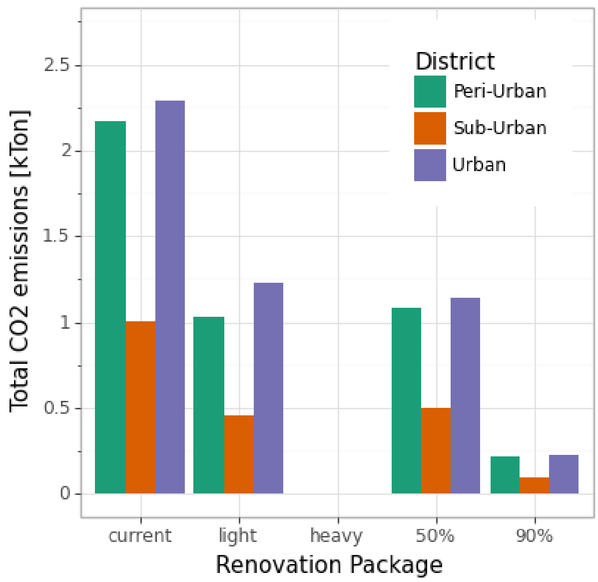

Figure 5 Total non-ETS CO_2 emissions as function of the renovation packages

In addition to the non-ETS only emissions, another extreme situation interesting to visualise is the one considering the current CO_2 intensity derived from electricity production. The results including the CO_2 emissions of electricity are shown in Figure 6. In the current situation, including ETS emissions (electricity) increases the average emissions by 5-15%. For the heavy renovation scenario, CO_2 emissions are 0.47 kton, 0.31 kton and 0.13 kton for the Urban, Peri-Urban and Sub-Urban district respectively. This is on average a reduction of 85% compared to the current situation. The 50% and 90% scenarios only reach reductions of respectively 49% and 79% compared to the current situation when CO_2 emissions of electricity are accounted for with the current CO_2 intensity for electricity. Note that the difference is highest for the 90% scenario as this relies heavily on heat pumps for which CO_2 emissions are assumed to be 0 when only accounting for non-ETS emissions.

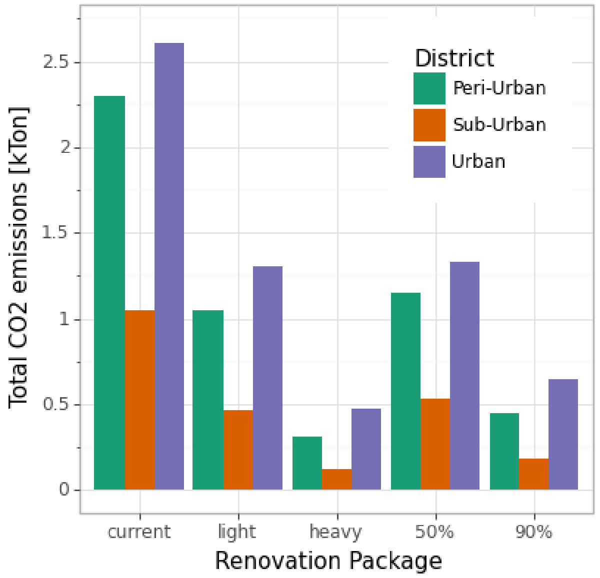

Figure 6 Total CO_2 emissions as function of the renovation packages. Results are including CO_2 of electricity based on the current CO_2 intensity for electricity production.

Investment costs (breakdown)

While previous graphs have focused on the effects of renovating the building stock, Figure 7 shows the breakdown of necessary investments for each of the districts for each renovation package. As expected – and in line with the results of the energy use – the highest absolute investment cost is found in the Urban district. This evidently follows the higher urban density, leading to more compact buildings. As a reference, Figure 8 shows the average investment cost per m² of floor area for the different scenarios. The highest values are observed for the sub-urban district which is characterized by a higher share of detached houses.

Another fact pointed out by Figure 7 and Figure 8 are the higher investment needs for the uniform scenarios. On average the total investment cost is 63% higher for the uniform light renovation scenario compared to the '50%' scenario. The difference is mostly caused by a significantly higher investment in wall insulation in the light-renovation package compared to the '50%' scenario. Besides, the light package did not foresee window replacement, which shows to account for a significant share of the total renovation budget in the '50%' scenario.

The total investment costs for the heavy renovation packages are on average 20% higher than those for the optimized 90% scenario. The '90%' scenario has lower contributions of roof and wall insulation while showing more window replacements compared to the heavy renovation package.

It is also interesting to point out that the differences between the uniform and optimized scenarios decrease as the CO_2 targets get more ambitious. This can be explained by the higher need for extensive retrofit in all buildings when ambitioning high CO_2 savings.

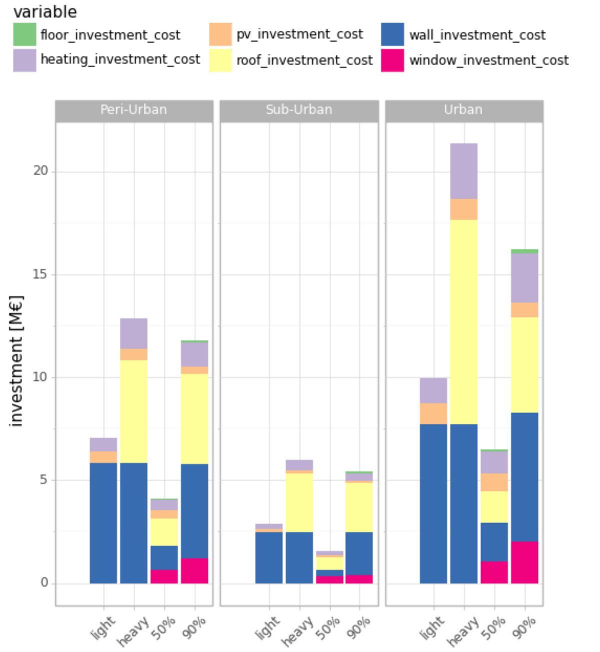

Figure 7 Breakdown of investment costs per district as function of the renovation packages

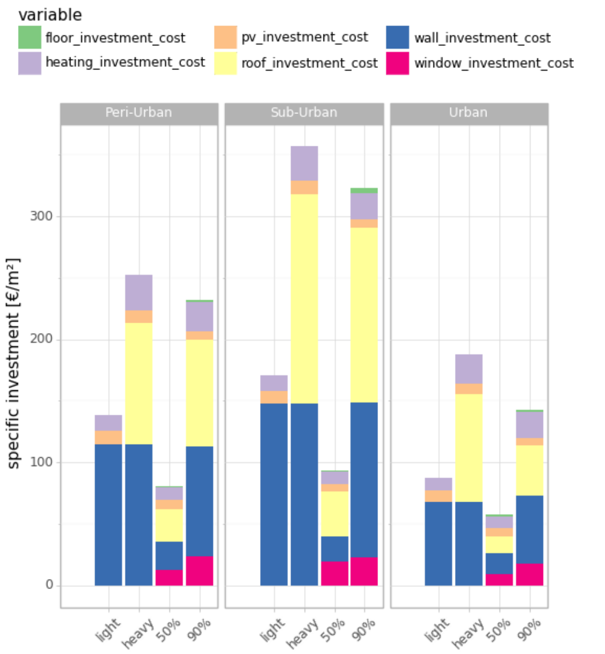

Figure 8 Breakdown of specific investment costs as € per m² floor area.

Total cost of ownership

When optimizing the district from a system perspective, it is interesting to find the technical solution for the district that minimizes the total cost of ownership over the total lifetime. Figure 9 shows the total cost of ownership over a 30-year lifespan assuming a 3% discount rate. Firstly, it shows that the heavy retrofit package and 90% scenario result in the highest TCO values. This demonstrates that for these heavy retrofit packages the significant increase in investment costs (Figure 7) are not compensated by equivalent energy costs savings compared to the 50% or light renovation (Figure 9). The high electricity price compared to the gas price does not support the shift towards heat pumps. It should however be noted that the consumer prices used are highly dominated by taxes and other non-energy-related costs.

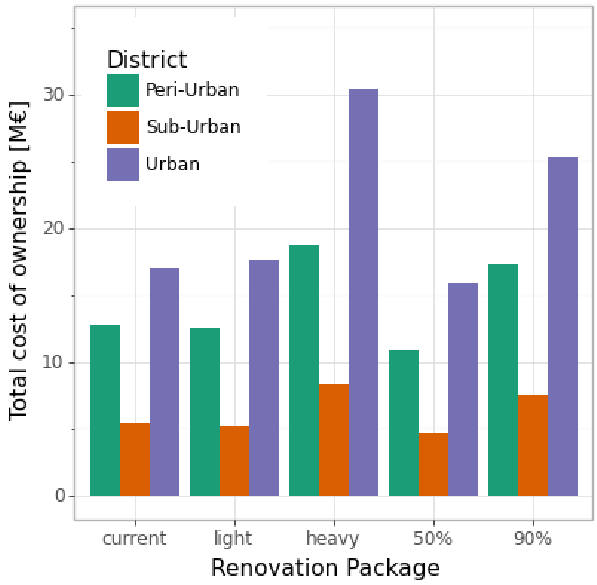

Figure 9 Total cost of ownership as function of the renovation packages, assuming a 30-year period and 3% discount rate

The results for the light retrofit and '50%' scenario do not significantly differ from the current situation. The latter assumes no extra investments, but only includes the energy costs over the next 30 years. The '50%' scenario slightly outperforms the light renovation package. The slightly higher energy costs for the '50%' scenario – due to the higher share of heat pumps – is outweighed by the significantly lower investment costs.

CO_2 abatement cost

As a final KPI the CO_2 abatement cost is analysed. This CO_2 abatement cost represents the cost of reducing CO_2 emissions expressed as the increase in total cost of ownership compared to the reference scenario divided by the total CO_2 reduction compared to that reference. Figure 10 shows significant variations between the district types and the renovation scenarios. Overall, abatement costs below 150 €/ton indicate that building retrofit is indeed a competitive measure for CO_2 mitigation.

The lowest abatement costs are obtained for the '50%' scenario with values of -50 €/ton for the Sub-Urban and Peri-Urban districts and -27 €/ton for the Urban area. These findings are in line with the results observed for the TCO and demonstrate that with current energy and technology prices a 50%, CO_2 reduction can be obtained in a cost-effective manner. The results also indicate that the uniform renovation scenarios result in abatement costs that are 20-80€/ton higher compared to the corresponding pareto optimal solution, with the highest costs for the heavy renovation package applied to the Urban district.

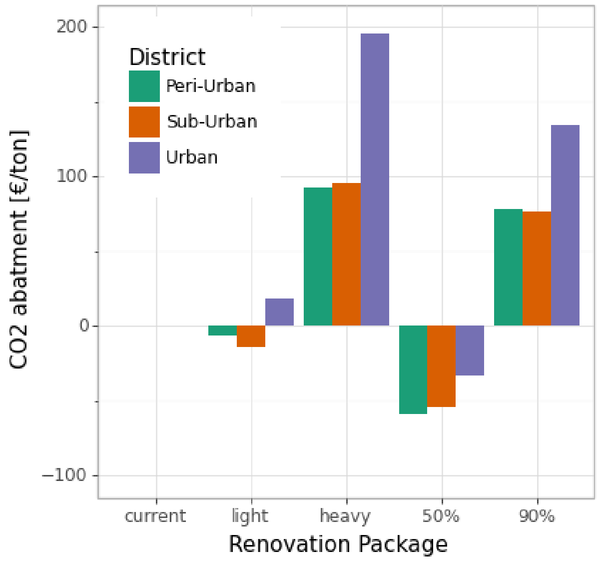

Figure 10 CO2 abatement cost as function of the renovation packages. Only considering non-ETS emissions

Discussion

CO_2 abatement costs are an interesting measure to compare different CO_2 mitigating technologies and solutions. In this work, the CO_2 abatement costs have been quantified for different district renovation scenarios, showing values which are competitive with current state of the art technologies. Current projections on ETS CO_2 prices for 2050 under respectively an 80% and 95% reduction path vary between 120 and 300 €/ton (Gerbert et. al, 2018). However, we need to stress that current simulations do not take into account the real energy consumption. Rather, they rely on theoretic assumptions - often conservative – for the indoor temperature levels and percentage of heated surface area in order to be in line with the national EPC calculation method. Comparison between predicted and measured consumptions display on average an overestimation of about 70%, meaning that in practice CO_2, abatement costs may be twice as high. Further research is therefore needed to extend the database with detailed real consumption information. While consumption data is today available for Flanders as open data on street or neighbourhood level, such aggregated data lacks the correlation between energy consumption, building parameters and occupant characteristics (e.g. household size, income…). Despite the difficulty in data-gathering, the approach demonstrated in this paper was found to provide valuable information on relative differences between the difference scenarios, facilitating fundamental support in the concretisation of policy recommendations on energy in buildings.

Conclusion

The Urban Energy Pathfinder was introduced as an urban energy simulation and scenario development tool to compare a wide variety or renovation options tailored to the concrete circumstances of a district. The methodology is based on a bottom-up energy simulation model and makes use of an intelligent data-model that combines GIS data on a wide variety of aggregation levels.

The UEP was used to compare 2 uniform renovation scenarios in which all buildings are subjected to the same renovation with 2 pareto-optimized scenarios in which the best possible combination or renovation measures is applied to reach a CO_2 emission target on district level.

The results show that up to at least 50% CO_2 emission savings can be reached for the investigated districts with a negative CO_2 abatement cost. For both, 50% and 90% CO_2 reduction targets the pareto optimized solution was able to reach a comparable level of CO_2 emission savings compared to the uniform renovations at significantly lower investment costs, demonstrating the potential of this type of scenario analysis tool to support policy development.

Acknowledgement

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