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Case study modelling for 9 urban districts in Flanders, Belgium

Position Paper

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Colophon

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List of abbreviations

BAU	business as usual
CAPEX	capital expenditures
CHP	combined heat and power (plant)
COP	coefficient of performance
DH	district heating
DHC	district heating and cooling
DHW	domestic hot water
EBECS	EnergyVille Building Energy Calculation Service
EE	energy efficiency
EU	European Union
GRB	grootschalig referentiebestand
HR	deep (heavy) renovation
HT	high temperature
LOD	level of detail
LR	light renovation
LT	low temperature
OPEX	operational expenditures
PV	photovoltaic
RE	renewable energy
SPF	seasonal performance factor
TCO	total cost of ownership
VEA	Vlaams Energieagentschap

Contents

Executive Summary

Urban retrofit is a major field of action for realising the European Union's energy and climate goals. The challenge laying ahead is complex: there is a wide variety of solutions that can be applied in different mixes, the related costs are high, and the social impact of the needed interventions is considerable.

With a view on identifying optimal urban retrofit strategies from both an environmental and an economic point of view, the present study analyses the trade-off between increasing the energy efficiency of the existing building stock on the one hand and supplying it with renewable energy and/or sustainable district heating on the other hand. Realizing higher levels of energy efficiency indeed allows to reduce the remaining sustainable energy needs and vice versa. But how to prioritize them?

Optimizations can lead to different choices depending of whether one focuses on reducing energy consumption, carbon emissions or costs.

Moreover, the scale level at which these questions are being addressed matters. A solution that is optimal at the individual building scale level may not be so at the district scale and vice versa. It is therefore important to understand where optimal solutions at the district level differ from those at the individual building level.

In order to model and subsequently assess these complex trade-offs, different urban retrofit scenarios have been simulated with a purpose-written Python algorithm, consisting of the EnergyVille EBECS simulation tool combined with certain extensions. Hereby different sets of energy-related interventions haven been modelled for 9 selected urban districts in Flanders: 3 central urban neighbourhoods, 3 peri-urban districts and 3 suburbs. Such case based comparison has allowed to account of, among others, the state of the present building stock and varying urban densities as important variables.

From a multitude of possible intervention scenarios, only combinations that are technically feasible have been selected. For example, when a district is set to be served by low temperature district heating while the buildings have only been lightly retrofitted, booster heat pumps are foreseen in order to upgrade the incoming low temperature heat towards a level that is suitable for the buildings in case.

The study considers contributing factors like the type of urban district (urban versus suburban), the depth of the building retrofit operation and the type of heat provision (different types of stand alone solution versus district heating network connection). The starting situation is one where natural gas networks are already present and have been (largely) depreciated, while district heating networks are absent. This puts natural gas networked solutions at a competitive advantage, but this is also the situation on the ground in large parts of Flanders – particularly in the urbanized areas which are the focus of this study.

Intervention scenarios are compared in terms of energy use, carbon emissions and cost. Hereby the standard assumptions are an investment horizon of 30 years, a 3% discount rate and 50% assignment of the building envelope retrofit costs to the energy aspect.

In this way a broad range of urban retrofit scenarios could be mapped, going from the simplest business as usual - only doing regular repair of buildings and not rolling out any district heating networks - to 'all-in' retrofit scenarios that combine deep building retrofit and renewable energy production with provision of sustainable heat via a district heating network.

The resulting energy figures, costs and benefits, and carbon emission reductions are being considered at the level of the urban districts. Following the system modelling perspective, the present study indeed aims at identifying the best overall solutions (total societal cost of ownership), yet not the optimal business cases and their related distribution of costs and benefits among the contributing parties (energy suppliers, grid operators, individual building owners, local authorities, ...).

Sensitivity analyses were performed to assess the influence of the degree of connection to a district heating network when it is present, the cost of the district heating source, and the share of building envelope retrofit costs being attributed to the energy aspect (considering half of the retrofit cost versus the entire retrofit cost as an energy related investment). The latter is important to investigate given the high cost of building envelope retrofit on the one hand, versus the fact that such retrofit not only benefits the energy performance, but also the indoor health and comfort, the state of repair of façades and roofs, the building's aesthetics and its real estate value. In this way retrofitting a building may not only be considered as an energy investment.

The targets to be assessed can be a combination of energy savings, carbon emission reductions and the lowest total cost of ownership from a societal perspective. With a view on realizing the EU energy and climate goals, it is in particular interesting to investigate how high emission reductions can be achieved while at the same time minimizing the total cost of ownership. It is also interesting to know how much low carbon scenarios cost, compared to business as usual – assuming that fossil fuels remain available at the price levels of today.

The effect of interfering in the current price setup for electricity, gas and fuel oil, for example by shifting taxes from electricity to natural gas and fuel oil, has not been modelled. Assessing how such interventions could change the business case for the solutions analysed in this paper, would however be a relevant subject for further research.

The present study does not elaborate on new constructions. As of 2021, all new buildings in the EU must be nearly zero energy, which makes their starting point fundamentally different. As the building envelope of most or all new buildings will be highly energy-conserving, much of the challenge resides in the choice for the energy installation, hereby taking into account the urban context: stand-alone solutions (mainly all-electric), versus networked solutions (be it a connection to regular district heating networks, microgrids or other solutions like biogas or syngas delivered through an updated natural gas network).

The results of the simulations regarding urban retrofit lead to the following conclusions:

Carbon lock-in

Without any tax or price incentives (including market price increases for fossil fuels), low carbon solutions will rarely be developed on the single basis of cost effectivity. Compared to business as usual or light retrofit scenarios where no district heating networks are being rolled out, only low cost, high temperature district heating network solutions may be competitive, and this only in certain urban areas. In the latter case, the district may thus become carbon-neutral if the district heating source is carbon-free, but it will at the same time continue to consume considerable amounts of energy. This implies that at current price levels for fossil fuels and with present tax distribution shares over electricity versus gas and heating fuel, there remains a deep societal lock-in for energy and carbon intensive functioning.

When explicit carbon emission reduction goals are set as a boundary condition, the picture changes substantially and shows a diversified palette of possible scenarios coming forward as feasible solutions. Hereby there appears to be no basic rule like 'always perform deep retrofit' or 'always roll out district heating networks in urban areas'. Temperature level and cost of the district heating source, as well as urban density, play an important role for distinguishing the options with the lowest total cost of ownership.

Where energy savings are targeted, it is obvious that only increasing energy efficiency brings real relief and hence deep retrofit of the building stock will be the best option – coming at a high cost however. In a second order, heat pumps may deliver additional energy efficiency as they rely only partially on accounted energy (the needed electricity) and for the rest utilize (unaccounted and for free) environmental heat. However, in order to be effective, these heat pumps need to operate in a context of low energy demand.

A general and major barrier for intervention is the high cost of building retrofit.

Energy savings may however be an important parameter for solving the regional 'energy puzzle', see below, and thus be necessary in any case.

Further research is needed to understand the widespread occurrence of low measured energy consumption figures in the sample districts, even remaining below the target 100 kWh/m² annual limit for space conditioning in the actual situation. It may be suspected that factors such as prebound and energy poverty play a role. Low actual energy consumption figures jeopardize the business case for retrofit in terms of potential financial savings and the related payback periods of energy efficiency measures, but do not change the case for improved comfort and better preparedness for a low carbon future.

Options for a low carbon future

If the intention is to avoid deep and expensive retrofit of the building stock while still realizing low carbon goals, the challenge is in providing sufficient amounts of sustainable or renewable energy for such approach. There are 3 possible scenarios:

1. **Stand alone:** the evident option, which is not considered in this study, is an individual biomass boiler for every building. For reasons of air quality and local availability of biomass, this solution must however be considered as the exception rather than the rule. The second option would be a heat pump, but given the high energy demand of the building this will come with technical challenges and/or high electricity uses. Biogas (supplied through the original natural gas network) will only occur in limited cases for reasons of limited biomass availability. For the majority of the buildings, low carbon stand alone will only work well through deep retrofit and a switch to all-electric functioning with heat pumps. The deep retrofit measures help moreover to limit the increase of the electricity demand by the heat pumps, and hence the need for grid reinforcements.

2. **High temperature district heating:** this is the most profitable scenario, as far as a carbon-free high temperature district heating source is available. Such source may be based on biogas or biomass (on a large scale, deployed with fume cleansing), solar heat, industrial waste heat or deep geothermal heat. These sources are only available at certain locations and/or in limited quantities, compared to the average societal heat demand. Moreover, and as the concerned buildings will typically not be deeply retrofitted to minimize the total cost of ownership, the heat demand remains high. This scenario is interesting but will in practice often have to be reserved for areas with no other feasible solution, e.g. heritage areas.

3. **Low temperature district heating:** buildings connecting to the network need to rely on a booster heat pump for upgrading the temperature level of the incoming heat. The operational cost of this scenario becomes very important, even to such level that the total cost of ownership of the solution is higher than for any scenario with deep retrofit

– deep retrofit combined with a heat pump as much as deep retrofit with a connection to a district heating network. Moreover, as electricity use for this scenario is substantial and adds up to the existing consumption of household appliances, the current electricity grid may require substantial reinforcing as well. The grid operator will recover these reinforcement costs from the end user. It will result in the individual building owner paying twice: once for the high electricity consumption and once more for upgrading the grid infrastructure.

By conclusion, when high carbon emission reductions are required, the only alternative for deep retrofit exists where (low cost) high temperature carbon-free district heating can be rolled out. If the district heating source becomes more expensive, the competitiveness of this solution slightly reduces. The feasible non-district heating variant using such source is individual heating with a biomass boiler. This solution should however not be promoted.

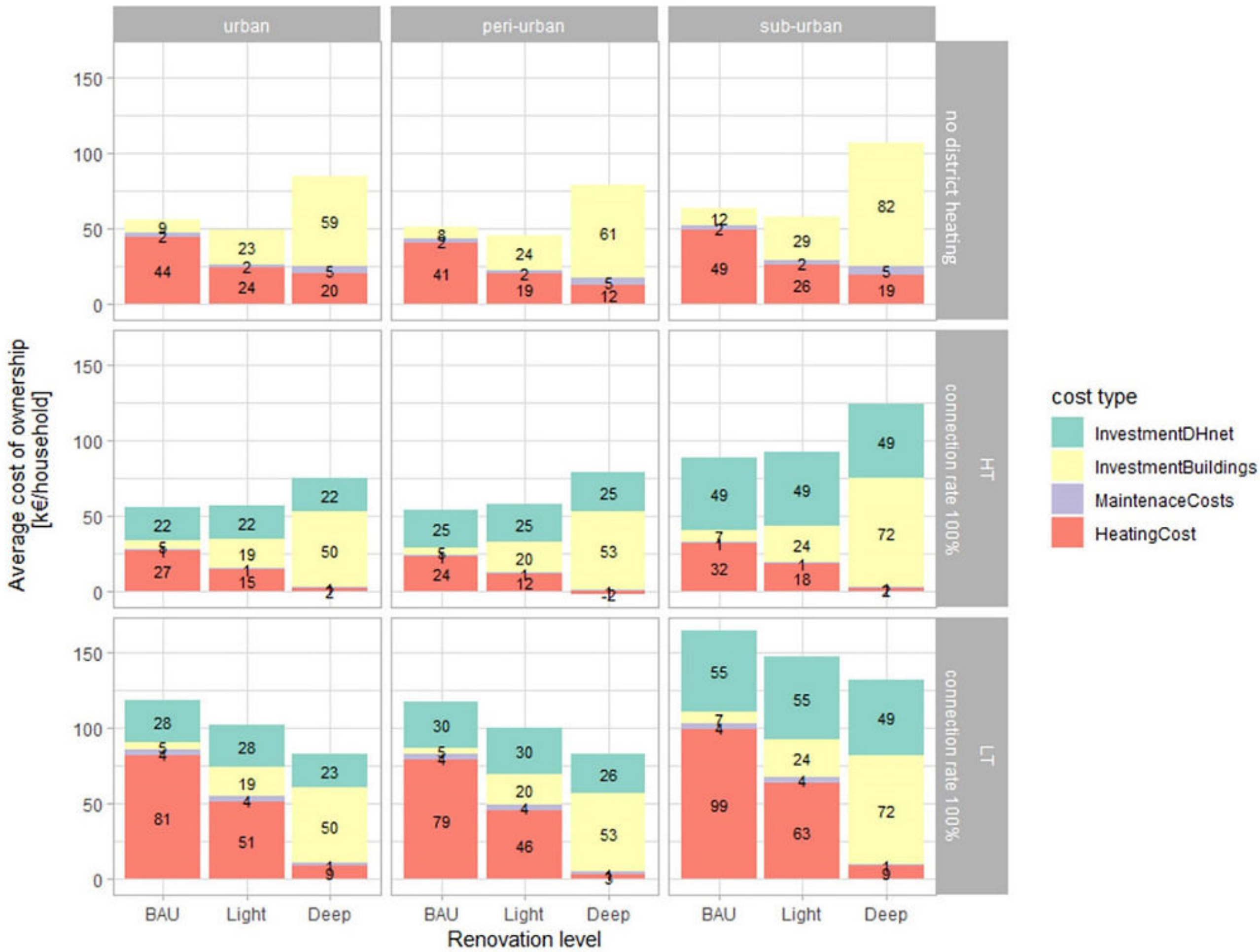

Figure 1: Breakdown of total cost of ownership among cost type (30 years horizon, 3% discount rate, 50% attribution of the envelope retrofit cost to the energy related aspects) for a low-cost, high temperature or low temperature district heating source with 100% connection rate to the district heating network, compared to no presence of a district heating system

Conclusions from the building perspective

From the perspective of the individual building owner, reverting to light renovation may often come forward as the most attractive option. This is a fortiori the case with low cost, high temperature district heating available. However, if the EU policy goals of 80 to 95% reduction of carbon emissions must be achieved, near 100% renewable energy input becomes mandatory. As a substantial share of the related thermal energy inputs will come at low temperature levels, there are only two major options for buildings:

- Perform deep retrofit and thus have the building fit for low temperature heating through a heat pump or through low temperature district heating. The retrofit operations can be performed stepwise, based on a building roadmap, in order to make investments more feasible. In this way these investments can moreover coincide with natural intervention moments such as sale of the building, necessary repairs or general renovation. A building roadmap is hereby strongly advisable in order to avoid sub-optimal interventions (lock-in). It must be noted that deeply retrofitted buildings are also more comfortable and healthy; furthermore they are better prepared for the use of heat pumps and demand response in a dynamic renewable energy provision context;

- Perform light retrofit and revert to the use of a booster heat pump to provide for both domestic hot water and space heating at the required high temperature level (65°C). Although this leads to savings on the building envelope retrofit costs, it leads at the same time to substantial electricity use and thus increased costs over the total life cycle. Total costs will finally outweigh the costs of deep retrofit scenarios.

If light retrofit would be performed as a first step towards later deep retrofit, it should be envisaged in such way that, both from the technical and financial point of view, no lock-in is created.

Conclusions from the district heating network perspective

Rolling out (low temperature, 4th generation) district heating is not an evident option when being considered on an investment horizon of 30 years. This adds to the need to consider district heating and cooling networks as assets in which society decides to invest based on a longer time horizon (typically starting from 40 years) and with particular goals in mind – the low carbon society and 100% renewable energy input in particular.

The influence of the connection rate to the district heating network is dependent of the type of network: high temperature versus low temperature. This is mainly due to the chosen set up of the scenarios, whereby badly insulated buildings need booster heat pumps to connect to low temperature district heating systems.

Resultantly, for high temperature district heating cases, the total cost of ownership only slightly increases with decreasing connection rates. The business cases are thus not fundamentally altering between a 50% and 100% connection rate. It means that once the district heating network has been rolled out, the advantage of connecting more homes exists but is limited, at least from the point of view of the total cost of ownership for society and not in terms of the business case for the district heating network operator. In urban areas, stand-alone, all-electric deep retrofit always remains more expensive except where buildings are systematically deeply retrofitted and at the same time only for 50% connected to the district heating system: this scenario is clearly a waste of means by sub-optimally introducing a 'double' solution.

For low temperature district heating cases, the total cost of ownership increases with increasing connection rates, especially where expensive booster heat pumps are needed for the business as usual or lightly retrofitted buildings. The contra-intuitive conclusion that more connections bring on a worse business case, is fully due to the situation that staying with a stand-alone, fossil fuelled home is cheaper than connecting it to a district heating system for which it is not prepared. Together with the high electricity price, this leads to a financial punishment for connecting to the district heating network. It remains however a solution that may make sense for lowering the overall carbon emissions.

For all scenarios it must be kept in mind that the availability of high temperature district heating will be the exception rather than the rule, for the following reasons:

- Availability of waste incineration as a cheap high temperature source will reduce over time as the circular economy takes shape. Waste heat shall in this perspective often be considered as a transition source. It will kickstart the roll-out of district heating systems, after which upgrading to other 4G sources will be made easier. A similar reflection could be made for a particular case in Flanders, the city of Antwerp, where a huge industrial waste heat potential is available from the petrochemical industry (an estimated 1000 MW at 80 to 120°C or more). We see an exceptionally good case for high temperature district heating roll-out, but with possible switches away from traditional fossil fuel-based production towards bio-based products, the future availability of this source may come under threat.

- Compared to the societal heat demand, biomass is only available in limited quantities especially if one adopts sustainability criteria implying that waste streams are the norm for energetic use of biomass and that virgin biomass shall in a principle not be used for energy production;

- In a similar vein deep geothermal energy can only be applied at given geographical locations and comes with higher costs and challenges as source depth increases;

- Solar boilers provide an attractive source but are expensive and equally limited in capacity (or need large deployment surfaces in order to provide heat in sufficient quantities);

Another important boundary condition relates to the seasonal heat balance. Heat sources like waste heat and solar heat lead to a seasonal balancing challenge: the heat production is continuous over the year or peaks in the summer whereas the demand peaks in the winter, causing the need to buffer heat over long periods. When buildings are not being renovated, the buffered heat shall moreover be available at high temperature which increases the challenges and related costs. At present the costs of buffering e.g. solar heat have been included in the heat cost (storage at an investment cost of 25 €/m³ in water-based heat buffers is feasible) but two other parameters nevertheless remain critical: the surface of solar collector fields needed, and the size of the related buffers. These have important spatial impacts and the available land or space may not be sufficient to fill in the demand when no reduction measures for the energy demand are being taken. Other factors like aesthetic objections are also expected to interfere.

Conclusions from the societal energy demand perspective

The current heat demand of the building stock is so high that in many cases sustainably supplying all required (carbon-free) heat for a non-retrofitted building stock will appear to be impossible, even if this supply is stretched to its technical limits (and thus making abstraction of limiting factors like the current spatial planning regulations regarding renewable energy production).

Moreover, the use of heat sources like waste heat and solar heat leads to a seasonal balancing problem which needs a specific (and costly) address, cf. supra.

All of these factors will push back to at least a partial retrofit of the building stock, be it for technical, spatial or financial reasons. Given the dependency on context, and more in particular the availability of sufficient low carbon district heating resources, only a case by case trade-off will reveal the real possibilities in situ.

In general, we can conclude that the real challenge does not reside at the level of the individual district, but at the urban or regional scale. It is at the higher scale level that the supply and demand of available (heat) resources command the viable options. Within those boundary conditions, sources and interventions must be allocated depending on every single context at the district levels.

A similar challenge appears for electricity: as on the one hand more PV is installed and on the other hand more heat pumps come into operation, the risk of daily or seasonal imbalance on the grid sharply increases. Again, this is a problem that must be solved at the higher scale levels and by bringing in additional features such as local electricity and heat storage.

Once the regional energy balances have thus been considered, decisions can be made to choose the lowest total cost of ownership solutions at the level of the individual urban districts. Depending on the location with its renewable energy potential, the urban density and the state of the building stock, switching to stand-alone and all-electric deep retrofit or to varying degrees of retrofit combined with district heating provision will come forward as the best option from a combined technical and financial point of view.

General conclusions

The above observations lead to the conclusion that, independent of the presence of district heating and cooling networks, it is in the long term recommended to perform a deep retrofit on all buildings except for those cases where, for particular reasons like heritage conservation or the close and ample availability of high temperature heat, reverting to a high temperature district heating network is the preferred option.

The incentive for deep retrofit of the building stock is however not only a matter of energy, but also of health, comfort, real estate value and future-proofedness.

The influence of the assignment rate of building envelope retrofit costs on the preferred choices is considerable. The adopted perspective on building investments (and hence, the adopted building roadmaps) is steered by multiple and strongly connected values. Whether we consider an intervention as just an 'energy burden' or as an investment in the building as a whole value asset, makes a substantial difference.

District heating networks must be considered as a solution that helps to realise the EU climate goals from a long term investment perspective. A careful local analysis must clarify where they will be preferably rolled out. Well-prepared heat zoning plans will therefore greatly support such strategy.

1. Introduction: goal and scope of the study

Interventions aiming at the realization of a low-carbon built environment must address both **energy efficiency (EE) and renewable energy (RE)** input. In fact, both aspects can be considered as two sides of the same coin: both contribute simultaneously and in mutually balancing ways to the energy equation. Realizing higher EE levels allows to reduce the remaining RE needs and vice versa. But how to prioritize them? Optimizations can lead to different choices depending on the indicator being prioritized: energy consumption, carbon emissions, total cost of ownership or return on investment are some examples. Moreover, the scale level at which these questions are being considered matters. A solution that is optimal at the individual building scale level may not be so at the district scale and vice versa.

In order to gain a deeper insight in the related trade-offs, we formulate a double research question:

1. Can this balancing problem be modelled using a concise set of input parameters, and;
2. depending on the outcome, can general principles for the EE-RE trade-off be derived, or can one only revert to context-specific solutions?

The present contribution investigates the different contributing factors and formulates a first set of conclusions based on ongoing simulation efforts and case studies.

Given the available technologies and from an urban point of view, an additional question is added to the EE-RE balancing problem:

3. in which urban areas would the preferential choice be to roll out **(4th generation) district heating and cooling networks**[1] (DH, DHC), and in which urban areas would switching to an all-electric paradigm (essentially based on heat pumps) without any DHC be preferable? Can guiding principles, design methods or rules of thumb be derived?

In order to obtain a structured insight in this problem the present analysis reverts to **nine case studies of urban built environment in Flanders, in three different contexts: central urban, peri-urban and suburban**, so as to arrive to a representative sample of urban settings.

The indicators being considered refer to final energy uses before and after intervention with related energy savings, cost figures, and carbon emission reductions.

The energy figures, costs and benefits, and carbon emission reductions are being considered at the level of **urban districts**. Following the system modelling perspective, the present study indeed aims at identifying the best overall solutions (total cost of ownership), yet not the optimal business cases and their related distribution of costs and benefits among the contributing parties (energy suppliers, grid operators, individual building owners, local authorities, ...).

The results should help local authorities in particular to set out urban retrofit strategies by providing better insights on the trade-off between investing in EE, connecting to a DH network and/or installing RE provision. Hereby it is equally important to understand where optimal solutions at the district level differ from those at the individual building level, so that appropriate policies and support mechanisms can be developed for realizing the most preferred outcomes.

The effect of interfering in the current price setup for electricity, gas and fuel oil, for example by shifting taxes from electricity to natural gas and fuel oil, has not been modelled. Assessing how such interventions could change the business case for the solutions analysed in this paper, would however be a relevant subject for further research.

The present study does not elaborate on new constructions. As of 2021, all new buildings in the EU must be nearly zero energy, which makes their starting point fundamentally different. As the building envelope of most or all new buildings will be highly energy-conserving, much of the challenge resides in the choice for the energy installation, hereby taking into account the urban context: stand-alone solutions (mainly all-electric), versus networked solutions (be it a connection to regular district heating networks, microgrids or other solutions like biogas or syngas delivered through an updated natural gas network).

1 Fourth generation DHC networks operate with a multitude of sustainable heat (cold) sources at lower (higher) temperatures and are smartly managed. For an analysis and definition, see Lund, H. et al (2014), 4th Generation District Heating (4GDH) - Integrating smart thermal grids into future sustainable energy systems, Energy, Volume 68, pp. 1-11.

2. Neighbourhood selection and characteristics

As a generic modelling exercise would be too complex, it was decided to select 9 representative patches of existing Flemish urban tissue for analysis. A patch consists of a circular area of 5 hectares (126,16 m radius) around a central coordinate.

The 9 patches represent 3 types of urban environment relevant for Flanders:

1. Central urban (3 cases);
2. Peri-urban (3 cases);
3. Suburban (3 cases).

All of the patches have a predominantly or exclusively residential character. Starting from this main characteristic, a maximum variety of contexts has nevertheless been aspired for the urban environment types.

The urban characteristics of every patch were extracted from existing databases by VITO's Environmental Modelling Unit (VITO-RMA). The data include spatial but also demographic characteristics like number of inhabitants and number of households, allowing to assess urban density figures. A verified subset of these data was used in the simulations.

The 9 patches are as follows (central coordinates in Belgian Lambert projection):

2.1. Central urban

1C. Antwerpen Berchem, centre point cultuurcentrum Berchem, Driekoningenstraat 126, 2600 Berchem, x = 153.759; y = 209.662

2C. Gent centre, centre point crossroads Stoppelstraat and Krommenelleboog, x = 104.247; y = 193.437

3C. Oostende centre, centre point crossroads Rogierlaan and Alfons Pieterslaan, x = 48.295; y = 213.863

2.2. Peri-urban

4R. Brugge Sint-Kruis, centre point crossroads Kloostermuur and Karel van Manderstraat, x = 71.179; y = 212.580

5R. Gent Sint-Amandsberg, centre point pharmacy Virginie Wauters, Toekomststraat 49, 9040 Gent, x = 106.384; y = 193.567

6R. Leuven Kessel-lo, centre point crossroads Koning Albertlaan and Jan Vandeveldelaan,
x = 175.022; y = 173.901

2.3. Suburban

7S. Hasselt Kiewit, centre point crossroads Europalaan and Henri Dunantlaan; x = 218.619; y = 183.513

8S. Roeselare, centre point De Gotelaar 5, x = 61.317; y = 184.748

9S. Grobbendonk, centre point crossroads Rubensstraat and Van Craeyenhemstraat;
x = 174.712; y = 209.221

A summary of characteristics of the districts is represented in Table 1.

ID	District	Number of inhabitants	Density of inhabitants (ha^{-1})	Number of households	Density of households (ha^{-1})	Surface of infrastructure (m²)
1	**Antwerpen Berchem,** centre Cultuurcentrum Berchem	1102	220	301	60	13400
2	**Gent centrum,** centre crossroads Stoppelstraat - Krommenelleboog	437	87	193	39	13800
3	**Oostende centrum,** centre crossroads Rogierlaan - Alfons Pieterslaan	701	140	358	72	13600
4	**Brugge Sint-Kruis,** centre crossroads Kloostermuur - Karel van Manderstraat	383	77	173	35	11500
5	**Gent Sint-Amandsberg,** centre pharmacy Virginie Wauters	802	160	306	61	11000
6	**Leuven Kessel-lo,** centre crossroads Koning Albertlaan - Jan Vandeveldelaan	449	90	145	29	11300
7	**Hasselt Kiewit,** centre crossroads Europalaan - Henri Dunantlaan	139	28	57	11	12000
8	**Roeselare** centre De Gotelaar 5	137	27	46	9	11700
9	**Grobbendonk,** centre crossroads Rubensstraat - Van Craeyenhemstraat	121	24	47	9	9500

Table 1: selection of spatial characteristics of the 9 districts (based on input by VITO-RMA)

3. Characterization of existing buildings and applied measures

3.1. Existing built environment

As the selected districts have a mainly residential function, and in order to reduce complexity, non-residential buildings or functions have not been modelled. All energy simulations relate to residential use profiles. Non-residential functions may however occur in residential type buildings, both in reality and in a modelling context. Therefore, a limited fraction of the building stock is not being accounted for in the analysis, or has been simulated by applying a residential use profile to it.

In a similar vein, individual houses that have been subdivided into apartments in reality, remain modelled as individual houses in the simulations.

The geometry of the existing buildings is automatically derived from the 3D Grootschalig ReferentieBestand (3D GRB)[2], using an algorithm developed at EnergyVille to overcome certain shortcomings of the 3D GRB source model. More precisely, this approach is as follows.

The model available in the 3D GRB extracts each building's footprint up to the height of the upper ridge, resulting in a simplified, prismatic 3D block geometry (level of detail 1 or LOD1). As the statistics show that most houses have a pitched roof, an extrusion over this ridge height causes a significant overestimation of the volume. Therefore, within the approach used in the present study, the volume of the highest storey is considered to be half of its original volume, assuming it to be under a pitched roof and being part of the heated volume. This approach is referred to as the LOD1 half-roof-based representation[3]. Note that the storey heights are unknown and thus need to be estimated as well. Although the LOD1 half-roof-based representation intends to take the roof shape into account, it is still not able to cope with building extensions. They are often lower than the main building volume. For buildings with flat roofs, the 'half-roof' operation results in a reduction of the (heated) building volume, but other factors like lower extensions in reality may still result in an overestimation of the volume at this point. The resulting overall deviation including underestimations and overestimations is judged to be within acceptable limits for our modelling exercise[4], and in any case preferable over the error margins of an archetypal approach.

We distinguish four building types: detached (D) and semi-detached (SD) dwellings, terraced houses (T) and apartments (A). The extraction algorithm for the geometry allows to differentiate among the four types, but with a specific rule for the distinction between terraced houses and apartment buildings: a building is judged to be an apartment building if the ridge height exceeds 12,55 m or if the house number in the street address is composite.

An error in the building type shares, in particular apartments versus others, will mainly affect the domestic hot water (DHW) demand in the simulations. Space heating is defined by the protected building volume, and simulated through a single temperature zone. In this way apartment buildings are also modelled as one single building with one thermal zone. Hence for space heating the building type and the number of inhabitants do not interfere with the energy demand. For DHW the situation is different. In the D, SD and T types one household is assumed to live in one building. This defines the DHW need based on family size. In apartments however the DWH need is based on, and proportional to, the building floor surface. Consequently, a deviation in the type assignments will have a minor influence and will not hamper the present modelling exercise.

Based on an expert judgement through visual analysis of each of the 9 particular districts, the building stock of a given district is proportionally divided into four selected age categories (before 1970; 1971-1990; 1991-2005; 2006-2011). Subsequently, all buildings of the district are randomly assigned to these age categories in the estimated proportional shares. As of an example, a suburban district that obviously dates from the 1960's and 70's will receive a 50% attribution for both categories 'before 1970' and '1971-1990'. The construction year attribution is needed to differentiate between building envelope characteristics, both in terms of original set up and renovations that have already been performed (see further).

The combined relevant building parameters (aside from the address data) are:

Building input:

- Construction year;
- Building type.

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2 https://overheid.vlaanderen.be/GRB-3DGRB . At the moment of the simulations, LIDAR data were not yet available in a processable form.

3 De Jaeger, I., Reynders, G., & Saelens, D. (2017), Impact of spatial accuracy on district energy simulations, in: Proceedings of the 11th Nordic Symposium on Building Physics (Vol. 132, pp. 561–566), Trondheim, http://doi.org/10.1016/j.egypro.2017.09.741; https://www.sciencedirect.com/science/article/pii/S1876610217348920?via%3Dihub .

4 The volume error of assuming that the building footprint is extruded over a height that is half a storey lower than the ridge height, compared to a fully detailed geometrical model that includes roof shape and building extensions, is found to be 12.6% on average, based on a district in the city of Genk of 700 buildings. Furthermore, the average error on the heated floor area is 14.2% and the average error on the total loss area is 7.6%. De Jaeger, I., Reynders, G., Ma, Y., & Saelens, D. (2018). Impact of building geometry description within district energy simulations. Energy, 158, 1060–1069. https://doi.org/10.1016/j.energy.2018.06.098

Geometry input:

- Number of floors (the number of full multiples of 3 m that enter into the ridge height);
- Floor area (number of floors times area of the building footprint);
- Protected volume based on the LOD1 half-roof-based representation;
- External building envelope:
  - Walls: 4 standard orientations (N, E, S, W) are being considered, which is a simplification of the real situation for each building[5];
  - Floor;
  - Pitched roof surfaces = 70% of total roof area[6];
  - Flat roof surfaces = 30% of total roof area;
  - Window area: 20% of the façade area except in shared walls. No horizontal or inclined windows and no separate door areas are taken into account.

The construction year (4 ranges) and building type (4 types) result in 16 categories used for further characterization. We however decline to use the term 'archetypes' for these 16 categories because the building geometry of every building is known and used in the simulations. By contrast, the categories are instrumental to represent a typical status of the building envelope and the installations for each given category, taking into account the standard renovation measures that often have already been applied in the present Flemish building stock. The categories have thus not only been modelled according to their original construction year characteristics, but assumptions on their present state of renovation have been included. These assumptions are based on a combination of available assessments and expert judgement. As such the building stock model differs from earlier simulations like in the Tabula study[7] and should be substantially closer to reality.

The resulting distribution percentages of each of the 16 categories in the 9 districts can be found in Table 2.

Categorization of districts		Construction year			
	Total number of dwellings	Up to 1970	1971 - 1990	1991 - 2005	2006 - 2011
District 1	345				
A	92	75	17	0	0
T	237	209	28	0	0
SD	15	15	0	0	0
D	1	1	0	0	0
District 2	249				
A	140	120	20	0	0
T	96	89	7	0	0
SD	13	13	0	0	0
D	0	0	0	0	0
District 3	192				
A	165	121	44	0	0
T	24	24	0	0	0
SD	3	3	0	0	0
D	0	0	0	0	0

5 Regarding simplification of calculations, see e.g. De Jaeger, I., Reynders, G., Ma, Y., & Saelens, D. (2018). Impact of building geometry description within district energy simulations. Energy, 158, 1060–1069. https://doi.org/10.1016/j.energy.2018.06.098). A full LOD2 model with the correct orientations was compared to a LOD2 with only 8 orientations and to a LOD2 with only 4 orientations. The impact for the district was small. The deviation on the annual energy demand was on average less than 0,4 percent. In the current simulations, a LOD1 with only 4 orientations is used.

6 Rounded share based on typological analysis, see e.g. Verbeeck, G., Ceulemans, W. (2015), Analyse van de EPC databank – Resultaten tot en met 2012, Leuven, where the observed split was 64%-36%. The EBECS calculation engine that is used for the simulations assigns a different U-value to flat and pitched roofs.

7 Typology Approach for Building Stock Energy Assessment, IEE project, 2009-2012, http://episcope.eu/iee-project/tabula/; see also De Jaeger, I., Reynders, G., & Saelens, D. (2017). Impact of spatial accuracy on district energy simulations. Energy Procedia, 132, 561–566. https://doi.org/10.1016/j.egypro.2017.09.741. The latter uses 'TABULA building envelopes' on which an additional correction is done for the simulations in the present study. Hereby retrofit operations such as roof insulation in existing buildings are taken into account, rather than assuming the original construction state.

District 4	187				
A	2	0	2	0	0
T	130	121	8	1	0
SD	42	36	6	0	0
D	13	12	1	0	0
District 5	279				
A	218	151	67	0	0
T	52	51	1	0	0
SD	8	8	0	0	0
D	1	1	0	0	0
District 6	179				
A	29	10	10	4	5
T	115	83	32	0	0
SD	35	27	8	0	0
D	0	0	0	0	0
District 7	70				
A	1	1	0	0	0
T	0	0	0	0	0
SD	45	19	26	0	0
D	24	16	6	0	2
District 8	61				
A	0	0	0	0	0
T	1	0	0	1	0
SD	2	0	0	1	1
D	58	0	25	24	9
District 9	60				
A	0	0	0	0	0
T	0	0	0	0	0
SD	4	3	0	0	1
D	56	37	17	2	0

Table 2: distribution of building types over the 9 districts.

The U-values for the building envelopes in their present state, taking into account common renovation measures that often have already been carried out, are defined as in Table 3.

For example, the U-value of 2 W/m²K for all windows indicates that we assume that by today (virtually) all single glazing has been replaced. This is of course not the reality, but still a generalization that is much closer to reality than e.g. assuming that all buildings from before 1970 have only single glazing[8].

Buildings constructed before 1990 will often have roof insulation added, compared to their original construction state. The nature and the thickness of the roof insulation packages however vary substantially. Based on available assessments a division is therefore assigned as follows[9]:

- 40% have the equivalent of 12 cm mineral wool or U=0,4 W/m²K
- 40% have the equivalent of 6 cm mineral wool or U=0,8 W/m²K
- 20% have virtually no insulation or U=1,7 W/m²K

8 Regarding glazing, sources at VEA and online sources like https://www.glaskoning.nl/blog/wat-een-u-waarde-van-glas; http://www.luchtdichtbouwen.nl/nieuws/u-waarde-en-r-waarde; https://www.habitos.be/nl/bouwen/u-waarde-van-glas-6097/ point to a range from 2,8/2,9 to 1,1/1,4 over the period 1980-2000s.

9 Assessments indicate that 80% of roofs have insulation by now: https://steunpuntwonen.be/Documenten_2012-2015/studiedagen/studievoormiddag-de-energiekwaliteit-van-het-vlaamse-woningenpark-kennisopbouw-aan-de-hand-van-de-beschikbare-data/1-de-energiedata-van-vea-over-het-vlaamse.pdf; 6 cm and 12 cm insulation thickness were equal in amount and most common in 2012: http://www2.vlaanderen.be/economie/energiesparen/epc/doc/Analyse_EPCdatabank.pdf. This led to the specific attribution of U-values for roofs in buildings older than 1990.

Category	Building type	Start year	End year	u_roof	u_wall	u_floor	u_window
A_0000_1970	A		1970	0,4/0,8/1,7	2,2	0,68	2
D_0000_1970	D		1970	0,4/0,8/1,7	2,2	0,85	2
SD_0000_1970	SD		1970	0,4/0,8/1,7	2,2	0,85	2
T_0000_1970	T		1970	0,4/0,8/1,7	2,2	0,85	2
A_1971_1990	A	1971	1990	0,4/0,8/1,7	1	0,68	2
D_1971_1990	D	1971	1990	0,4/0,8/1,7	1	0,85	2
SD_1971_1990	SD	1971	1990	0,4/0,8/1,7	1	0,85	2
T_1971_1990	T	1971	1990	0,4/0,8/1,7	1	0,85	2
A_1991_2005	A	1991	2005	0,4	0,5	0,7	2
D_1991_2005	D	1991	2005	0,4	0,5	0,7	2
SD_1991_2005	SD	1991	2005	0,4	0,5	0,7	2
T_1991_2005	T	1991	2005	0,4	0,5	0,7	2
A_2006_2011	A	2006	2011	0,3	0,4	0,4	2
D_2006_2011	D	2006	2011	0,3	0,4	0,4	2
SD_2006_2011	SD	2006	2011	0,3	0,4	0,4	2
T_2006_2011	T	2006	2011	0,3	0,4	0,4	2

Table 3: assumed U-values for the existing building envelopes

3.2. Applied retrofit measures

Starting from the existing situation in each district, several interventions are simulated. These interventions belong to the three following types:

1. Building retrofit measures, reducing the final energy demand;
2. Renewable energy production at the building scale;
3. Connection to a district heating system.

The selected building retrofit measures are grouped into one light and one deep renovation package. This will allow to assess whether deep urban retrofit is recommended for a given context, or not. The composition of the two packages is represented in Table 4.

Renovation package	Measures
Light renovation	▪ Roof insulation: extra insulation is placed until the U-value meets the target of 0,24 W/(m²K) ▪ Windows: new windows with U_f=1,5 W/m²K and U_g= 1,0 W/m²K, resulting in an average U_W = 1,1 W/m²K. ▪ Cavity wall insulation: not or partially filled cavity walls (U>0,6 W/m²K) are filled, resulting in U = 0,6 W/m²K. ▪ Condensing gas boiler ▪ PV system (sized to cover annual domestic electricity use)

Deep renovation	▪ Roof insulation: sarking roof is placed for pitched roof and extra insulation for flat roof until the U-value meets the target of 0,16 W/(m²K) ▪ Windows: new windows with U_f=1,5 W/m²K and U_g= 1,0 W/m²K, resulting in an average U_W = 1,1 W/m²K. ▪ External wall insulation: resulting in U = 0,16 W/m²K. ▪ Floor insulation: for buildings with a basement or crawl space, the floor is insulated to U = 0,24 W/(m²K) ▪ Air-water heat pump system that provides both space heating and domestic hot water. ▪ Ventilation system C+ (exhaust ventilation fan with demand control) ▪ PV system (4,1 kWp) to cover domestic electricity use ▪ Solar thermal collectors (4m²)

Table 4: applied retrofit measures

It is assumed that 30% of buildings have a basement or a crawl space, which is a conservative figure. If such a building is deeply retrofitted, then it receives the insulation package up to U = 0,24 W/(m²K), otherwise not.

It is to be noted that deep renovation packages will lead to a carbon-neutral performance as far as the electricity intake from the grid is carbon-free at the same time. Light renovation packages as modelled here remain dependent on a gas condensing boiler, and must thus be considered as not really future-proofed.

In the simulations these retrofit packages will be compared to BAU scenarios that include certain interventions as well. The latter regard roof and boiler replacement but shall be considered as regular maintenance and not as an energy retrofit, see also 4.1.1.

3.3. Characterization of energy uses before intervention

The engine used to calculate the energy performances of the individual buildings is EBECS, an algorithm developed at EnergyVille. Although it permits to recalibrate predicted performances (mainly depending on building envelope and installation characteristics) by means of real energy consumption data, this has not been applied for the present simulations. The reason is the rather widespread occurrence of low consumption data in the sample districts, even remaining below the 100 kWh/m²year limit for space conditioning which already complies with the long term goal put forward by VEA, the Flemish Energy Agency. It has not been researched what the mechanisms are behind these low consumption figures, but it may be suspected that pre-bound as well as energy poverty play a role, the latter presumably in certain districts. Hence, applying the real consumption figures would kill the financial case for renovation because there are few or no energy savings to be capitalized on (assuming a rebound effect after renovation). Therefore, EBECS has been run simulating energy performances based on the building and installation characteristics only, and independently from user behaviour.

Furthermore, the following assumptions and distributions have been applied:

- The share of natural gas use per street is divided over a fraction of the dwellings in the street, typical for the given urban context:
  - Central urban: 80 % of the dwellings have natural gas heating;
  - Peri-urban: 70 % of the dwellings have natural gas heating;
  - Suburban: 60 % of the dwellings have natural gas heating;
- Regarding existing gas boilers, overall 60 % are assumed to be condensing and 40 % non-condensing in the present situation;
- Regarding DHW, 33% is supposed to be produced using electricity and 66% on fuel oil or gas;
- Other uses: all dwellings not using natural gas for heating are assumed to use fuel oil (respectively 20%, 30% and 40% of the dwellings in the district).

These modelling assumptions are based on existing reviews of the share of gas versus fuel oil in the heating market, and the likeliness of a location (central urban, peri-urban, suburban) to have a high rate of natural gas network connections. Hereby some simplifications have been introduced, for example by omitting minor or marginal heating modes[10].

Some renewable energy production is already present in the existing neighbourhoods, mainly in the form of PV-installations. A visual analysis of the aerial photographs of each urban patch indicated a maximum share of around 20% of the dwellings having PV (or solar boilers), but the shares vary substantially over the different districts. It was decided to run the simulations assuming no PV or solar boilers are present before intervention. This would still coincide with a standard starting situation.

3.4. Energy input and production options

We consider three types of energy input and/or production:

- Standard (mainly fossil fuel based) installations: natural gas for heating, fuel oil for heating, electricity from the grid. Direct use of fossil fuels only occurs for the existing/BAU situation and for light retrofit. Deep retrofit involves no direct fossil fuel inputs but will be carbon-free depending on the characteristics of the electricity and/or heat taken from the grid;
- Renewable energy production: photovoltaic panels, solar boilers. Parameters like orientation are assigned according to the actual orientation of the roofs (excluding north);
- Potentially sustainable energy inputs: ambient heat through heat pumps, district heating.

Biomass boilers are not included in the sustainable heat production options. The general policy approach underpinning this choice is not to promote the individual combustion of biomass for reasons of air quality[11]. Biomass boilers may however be a responsible choice where they are applied as large scale (collective) installations with exhaust fume cleaning. However, even so, and from a macro scale point of view, biomass and biogas should be considered as exceptional rather than common energy sources for reasons of limited (sustainable, local) biomass/biogas availability compared to the total societal heat demand[12].

The differentiation of the district heating inputs has been set up as follows:

- Low temperature (LT, 30 to 40°C) or high temperature (HT, more than 65°C);
- Low, medium or high heat production cost (respectively 13, 32 or 42 €/MWh)[13];
- Assuming a connection rate to the network of 50%, 75% or 100%.

By the nature of the heat sources, not all combinations are fit for realising the EU energy and climate goals. Based on the principle that fossil fuels will be phased out and that sunk investments in gas fired infrastructure shall be avoided whenever possible, we do not consider natural gas fired boilers or CHPs as a desirable heat source for DH[14]. A basic set of feasible options for DH combinations thus becomes:

- HT, low cost: waste incineration, industrial waste heat, green gas in CHP;
- HT, medium cost: biomass, green gas in CHP;
- HT, high cost: solar boilers, deep geothermal energy;
- LT, low cost: waste heat;
- LT, high cost: heat pumps.

10 References: http://www.livios.be/nl/bouwinformatie/techniek/energiebronnen/aardgas/gas-vs-stookolie-de-cijfers/; https://www.mazout-on-line.be/nl/nieuws-over-mazout/verwarmingsinstallatie-voor-mazout/een-belg-op-vier-vertrouwt-op-huisbrandolie/ . The general tendencies are a higher rate of gas connections in urban areas (better or since longer serviced by gas networks) and a declining share of fuel oil over time, which becomes clear through the different information sources.
A source that was not initially consulted brings forward slightly different figures for the share of condensing boilers and DHW production modes, but these differences are not essential for the present modelling exercise. It concerns a survey among 1000 households with a respons rate of 57%. Amongst others, the survey confirms the rising share of (natural gas) condensing technology. See KANTAR TNS, Het energiebewustzijn en -gedrag van de Vlaamse huishoudens 2017, survey ordered by VEA, https://www.energiesparen.be/sites/default/files/atoms/files/grafisch%20rapport%202017.pdf.
Heating sources with a small or marginal share have not been modelled. The latter mainly include direct electrical heating (about 7-8% of the dwellings) and wood stoves (about 3-4% of the dwellings). See e.g. the sample results of KANTAR TNS, p. 77

11 Vlaamse Milieumaatschappij (2017), Stookadvies als maatregel tegen luchtverontreiniging door houtstook.

12 See e.g. Van Esch, L. et al (2016), Eindrapport Hernieuwbare EnergieAtlas Vlaamse gemeenten, VITO, https://www.lne.be/atlas-hernieuwbare-energie, pp. 43-50 and 79-81; Van Esch, L. et al (2016), EnergieAtlas Limburg, VITO, http://ftp.limburg.be/bestandenlimburgbe/ruimtelijkeordening/energieatlas_limburg_eindrapport.pdf, pp. 100-104.

13 This cost includes CAPEX and OPEX. If thermal buffers are needed, e.g. for seasonal storage, these are included in the CAPEX as well.

14 As a matter of fact, the simulations consider the temperature level and the cost, so these do not exclude source choices like natural gas as far as the latter are compatible with the selected temperature and cost figures. The DH options put forward here are therefore mainly a principal choice or advice.

A main consequence of the difference in temperature regimes comes for DHW: with low temperatures a heat booster is necessary, with high temperatures it is not.

Besides this, LT heat is not suited for space heating of poorly insulated houses and therefore in the simulations LT DH input will only be combined with deep renovation schemes (HR or deep renovation) or else (LR or light renovation and BAU), with a booster heat pump that serves both DHW production and space heating. The booster heat pump thus upgrades the incoming DH heat from LT to HT for all applications in the case of BAU and LR.

Summarizing,

- In case of district heating and deep renovation, heat pumps and solar boilers are removed from the applied renovation package;
- in the case of HT district heating no booster devices are needed;
- in the case of LT district heating
  - an electric resistance booster heater is foreseen to increase DHW temperature for deeply retrofitted buildings;
  - a booster heat pump (assumed with a fixed COP of 3) is implemented to increase heating and DHW temperature for BAU and light renovation.

When a building is prepared for LT servicing through deep retrofit, costs are calculated assuming no replacement of existing radiators and piping by floor and wall heating systems is needed, hence avoiding the break-up of existing floors and walls which would be a major barrier both from the financial and the logistic point of view (ability to continue to live in the dwelling during retrofit operations). The arguments for doing so are that (1) often in existing buildings radiators are already over-dimensioned from the outset and (2) while deeply retrofitting the building envelope, the energy demand is dropping in such way that the existing radiators can handle the remaining heat demand provision at lower temperatures[15].

Providing a DH solution includes the DH network, the connection with the dwelling and a booster device (electrical after-heater or heat pump) for the additional heating of domestic hot water (DHW) and space heating where needed.

We assume there is no active cooling demand as we consider residential buildings only in a moderate European climate.

These energy inputs need to be balanced against energy saving measures, which is the subject of the present analysis.

15 See e.g. Østergaard, D. S., Svendsen, S. (2016), Case study of low-temperature heating in an existing single-family house - A test of methods for simulation of heating system temperatures, in: Energy and Buildings, Vol. 126, pp. 535-544, https://orbit.dtu.dk/en/publications/case-study-of-lowtemperature-heating-in-an-existing-singlefamily-housea-test-of-methods-for-simulation-of-heating-system-temperatures(1b8af2ae-8ba2-4cc6-aaca-f4bb1d49814f).html and Østergaard, D. S. (2018), Heating of existing buildings by low-temperature district heating, PhD thesis, DTU, https://www.researchgate.net/publication/329308971_Heating_of_existing_buildings_by_low-temperature_district_heating

3.5. Cost figures

3.5.1. System perspective

The perspective adopted in this study considers the **total cost of ownership (TCO) for society** for each of the proposed measures or combinations of measures.

This implies that cost figures include investments (or CAPEX) and operational costs (or OPEX) over the considered **investment horizon of 30 years**.

Costs and benefits are thus considered at the aggregated level. Actor specific costs and benefits are not being analysed; in this way the business case for an individual home owner or for a district heating network operator is not being researched, nor are commercial profit margins being considered. This would however be possible while further elaborating on the present study.

When figures 'per household' are presented, this regards the societal TCO per household and thus represents an overall, average figure that may include costs (or benefits) that are not directly carried (or perceived) by the households themselves.

A **discount factor of 3%** is applied to the simulations. In an aggressive economic context, discount rates up to 20% are considered normal, whereas for 'societal economics' figures around 3-4% are commonly accepted[16]. Given the long term societal importance of climate action, we adopt a discount rate of 3%. The effect of not applying a discount rate at all is subsequently assessed in the sensitivity analyses.

The cost figures of measures have been mainly derived from internal expert consultations, and in a second degree from a variety of sources available online, from outputs of other EnergyVille projects and feasibility studies, and from specific retrofit project cost figures. The main rationale behind this approach was to collect prices of measures directly from the practice of building and installation contracting. In particular, the price specifications and differentiations go much further than current standard assumptions on average costs for building retrofit.

It can be argued that another approach, using general (statistical, sector, ...) data holds the risk of including many cumulative assumptions that do not guarantee a better result than the expert-based cost estimating approach used here.

At this stage no economies of scale or learning effects have been taken into consideration, which results in safe estimates of the cost of building retrofit. The prices apply to a Flemish/Belgian context.

The cost figures (including a renovation tax rate of 6%) for the considered interventions are thus as follows:

3.5.2. EE – Retrofit

Today most building envelopes have been insulated to a certain degree, typically varying with the year of construction: recent buildings have complete insulation packages from the outset, older buildings commonly have some roof insulation added at a later stage and simple glazing being replaced by double glazing. The retrofit interventions are proposed taking into account this situation:

Building envelope

Pitched roof insulation:

- **Pitched roofs** from older buildings would often have an insulation layer of some 6-10 cm of mineral wool or equivalent, typically placed between the existing rafters. Newer buildings have the insulation package according to the norms of the year of construction.
- **Light retrofit:** insulating the roof from inside (assuming there is an underroof present otherwise for reasons of building physics this intervention is not recommendable). We assume some 15-20 cm of glass wool can be put, including a wooden supporting structure as this insulation package is thicker than the standard 7 x 7 cm rafters of the roof structure. This intervention is estimated to cost **75 €/m²**.
- **Deep retrofit:** completely replacing the roof following the sarking principle: removing the old roof until the supporting structure, then putting sandwich panels, battens and new roof tiles or slates. The cost of this intervention is estimated at **270 €/m²**. In the unit price per m², a supplement for border finishes and other construction details is included.

16 E.g. Ochelen, S., Putzeijs, B. (2008), Milieubeleidskosten - Begrippen en berekeningsmethoden, Vlaamse Overheid, Departement LNE (p. 26-29), https://www.lne.be/sites/default/files/atoms/files/Milieubeleidskosten%20-%20begrippen%20en%20berekeningsmethoden.pdf and recommendations by the European Commission for the social discount rate, see European Commission, Directorate General Regional Policy (2008), Guide to Cost Benefit Analysis of investment projects, https://ec.europa.eu/regional_policy/sources/docgener/guides/cost/guide2008_en.pdf, pp. 207-210

Flat roof insulation:

- Light retrofit: often for many practical reasons (roof borders, gutters, door/window sills, ...) the insulation thickness that can be added is limited. Typically no more than 10 cm of wool or foam and a new roofing layer could be added. In addition roof borders need to be reworked. The cost of this intervention is estimated at 100 €/m².

- Deep retrofit: in this case the insulation package will be substantially thicker and the corresponding retrofit of roof borders etc. more substantial. The cost of this intervention is estimated at 200 €/m².

Exterior wall insulation

- If an exterior wall already has insulation, the case for adding insulation is weak. The intervention is very expensive compared to the relative improvement.

- Light retrofit: this is possible when an existing cavity wall has no insulation. The cavity can be filled with an insulation material at an estimated cost of 30 €/m².

- Deep retrofit: this implies adding a layer of insulation on the outer side of the existing façade, plus providing a new façade finishing (crépi; boarding, panels or slates on a supporting framework,...). All border details at the level of windows, roofs,... must be reworked accordingly. The cost of this intervention is estimated at 180 €/m².

Changing windows & doors

- We will consider a standard solution with high performance double glazing. Triple glazing is a more expensive solution at the level of very low to zero energy houses and as such considered to be out of scope for the standard retrofit interventions we envisage.

- Common retrofit solution: we assume that window frames must be replaced together with the glazing, which is the safer option. The intervention also includes providing ventilation grids where appropriate. The cost of this intervention is estimated at 600 €/m².

Insulating floors

- The technical situation in situ defines very much how difficult and expensive this operation is. We assume that floor insulation will only be installed in the case of deep retrofit and where this is easily done by adding an insulation package at the down side of the floor construction (i.e. in basements and crawlspaces). In this way floor insulation comes with a price tag of 30 €/m².

Natural gas based heating installations

- Individual condensing boiler, natural gas: a basic boiler with instant DHW production would cost 3.500 €; a heating boiler with a DHW buffer included would cost 5.000 €. As the buffer is a comfort option, we keep to the basic setup at 3.500 €. In retrofit scenarios fuel boilers and non-condensing gas boilers are always replaced by condensing gas boilers if gas is chosen as the heating source;

- Collective condensing boiler, natural gas: it has not been possible to derive a formula that models the price scale advantage in function of the number of housing units for common installations. Therefore, assuming a linear contribution of 3.500 € per household is a conservative option. In the simulations this was modelled by adding 3.500 € of boiler investment cost per 3 inhabitants. As the average family size in Flanders is only 2,3 persons, this somehow compensates for not including a scale advantage for collective installations.

Attribution of building retrofit costs to the energy aspect

As buildings need periodic maintenance, repair and replacement of components independent of any energy-related improvements (in particular roofs, windows and technical installations); and as comfort and real estate value increase when an energy retrofit is performed, not all of the intervention cost should be attributed to the energy aspect alone. We therefore apply a 50/50% attribution key as follows: 50% of the building envelope insulation costs are assigned to the improvement of the energetic performance, while the other 50% is attributed to the regular retrofit/repair actions and to the increased real estate value and comfort.

Heating installations are considered at 100% cost because they are a purely energy-related asset. The same holds for RE production (PV, solar boilers), see further.

A sensitivity analysis is performed for selected cases, where 100% of the building envelope retrofit cost is assigned to the improvement of the energetic performance.

3.5.3. RE provision

PV & solar collectors

- PV-panels [4.1 kWp]: we foresee a typical household installation at 4.000 € for the panels, inverter, installation and taxes, however excluding the prosumer tax which is currently applicable in Flanders.
- Solar collector: the optimum size depends on the family configuration. A four person family would need an investment of 5.500 €. In central urban locations we assume smaller families and therefore boiler installations of 4.000 €, which we will take as the reference intervention for all cases. We count with a renovation situation where there is some extra labour required to put new piping in an existing house.

Heat pumps

- We only consider air bound heat pumps, as ground bound heat pumps currently remain far from the economic optimum and provoke a lot of practical hassle (drilling piles in existing basements or digging up existing gardens) in a retrofit situation.
- The investment for an individual air bound heat pump, to be connected to an existing distribution system, is estimated at 8.000 €. No new radiators or floor heating systems need to be installed.
- For the investment in a collective air bound heat pump we adopt the same approach as for the collective boilers, i.e. a modular price of 8.000 € per 3 inhabitants in the building.
- The cost of a booster heat pump as applied for upgrading a LT DH input to a sufficiently high temperature level for both space heating and DHW is estimated at 5.000 €.
- The cost of a booster electric DHW heater for upgrading a LT DH input is estimated at 500 €.

3.5.4. Connection to a DHC network

The costs considered for the DH solutions include CAPEX and OPEX. In this sense, the operational heating costs appear as a production cost for the heat provider rather than a final energy cost paid by a customer connected to the DH network. This is compatible with an approach where the total cost of ownership for society is being considered and commercial margins are not being taken into account.

The CAPEX include the costs for building the DH network, i.e. the material and labour costs for the pipes, costs for connection and substations at the building level and engineering costs (assumed at 20% of the total CAPEX). To calculate the network costs, the network topology is generated assuming the main heat supply to be located at the centre of the district. Pipe dimensions and corresponding costs are then computed assuming commercial data for material costs and a 500 €/m cost for road works etc. Connection costs for the residential buildings include the pipe and labour cost and the substation and average at 8000 € per building. For the low temperature district heating scenarios booster heaters are installed for domestic hot water and – if required – space heating, cf. higher.

Note that placing the main heat source for district heating at the geographic centre of the district may not be feasible nor desirable in practice. Nonetheless, when comparing the total cost of ownership of the resulting district heating solutions to those of the all-electric solutions, this assumption allows to identify the investment potential for the heat source by taking the difference between the total cost of ownership of the all-electric solution and the district heating solution calculated under this assumption. In other words, when the all-electric solution for a district is more expensive, the gap between the total cost of ownership of that all-electric solution and the district heating solution with heat source at the centre of the district, is an upper limit for the budget available to harvest and couple into a heat source (e.g. waste heat, deep geothermal…) in the proximity of the district.

The heat production costs (OPEX) include the investments and production costs for the heat supply, eventual (seasonal) heat buffering (e.g. in the case of solar boiler arrays[17]) and other related exploitation costs[18]. For the OPEX, we refer to 3.4 for the three retained cost levels, low, medium or high heat production cost (respectively 13, 32 or 42 €/MWh). These have been derived from an assessment as presented in Figure 2.

17 A remarkable example of a solar collector array with 200.000 m³ heat buffer in a water reservoir can be found in Vojens, Denmark: http://arcon-sunmark.com/newsandmedia/vojens-district-heating-denmark and http://arcon-sunmark.com/cases/vojens-district-heating.

18 This approach, and in particular including both the investment and production costs for the heat supply, corresponds to standard practices in the DHC sector.

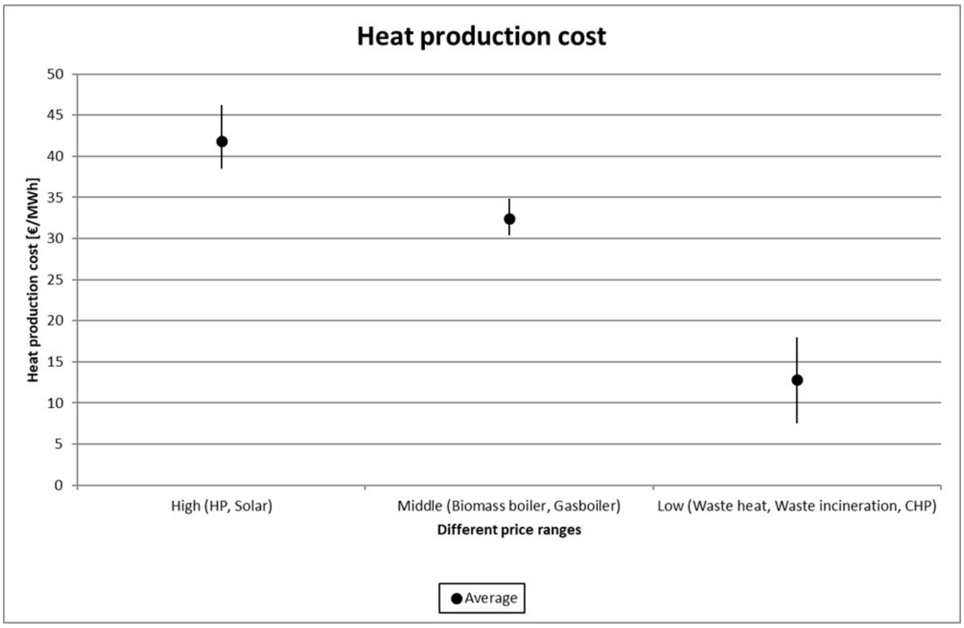


Figure 2: Heat production cost categorization. The figures are based on (commercial) price offers, feasibility studies, reference projects and other price indications available to the TES team at EnergyVille. Prices for biomass may vary considerably. Therefore, an average figure has been applied.

4. Scenarios

4.1. Applied scenarios and their respective boundary conditions

4.1.1. Base case and intervention scenarios

In order to develop an insight in the energy performance, CO_2 savings and financial costs and benefits of retrofitting on the one hand (increasing EE) and inputting renewable energy sources (RE) or district heating (DH) on the other hand, a series of intervention scenarios has been elaborated.

For all districts and study cases these scenarios will be compared to a **baseline scenario, business as usual (BAU)**, that includes the following elements:

- Taking into account the 30 years investment horizon, one replacement of each building's roof;
- and one replacement of the heating boiler, both interventions to be considered as **default maintenance** that would be undertaken in any case where the building owner does the proper building management.

The **intervention scenarios apply EE, RE and DH measures in different combinations** in order to provide for a **comparative analysis** and define the **trade-off points** that are the subject of the present study.

Only intervention scenarios that make sense from both the techno-economical and the environmental perspective are being investigated. Therefore, where a DH system is rolled out and a building is connected to it,

- the possible heat pump foreseen for that building is eliminated from the retrofit package, as the heat pump is no longer needed. The electricity use by the heat pump is transferred to energy demand for the DH system taking into account the seasonal performance factor (SPF) of the heat pump;
- in the case of LT DH:
  - with HR (which is LT compatible), a DHW booster (electrical after-heating) is provided. In this way 45% of the DHW heating demand is set to be covered by this booster. The corresponding fraction of energy is eliminated from the DH heating demand;
  - with LR or BAU (which are not LT compatible), a booster heat pump is provided to upgrade the DH input to a HT level suited for both DHW and space heating. In a similar vein, energy demands are transferred taking into account the proper SPFs (corresponding with a COP of 3 for the heat pump).

4.1.2. Costs

As mentioned higher and regarding both the baseline and the intervention scenarios, **50% of the building envelope retrofit costs are assigned to the energy aspect** (however, with a sensitivity analysis at 100% attribution, see further). This does not hold for building energy installations (classical boilers, PV, solar boilers); the latter are, cost wise, always fully attributed to the energy aspect.

In a principle the cost of (historically) rolling out the natural gas network should also be accounted for in the analyses. This has not been done, i.e. the gas network has been considered as entirely depreciated. This puts natural gas based scenarios at a slight advantage but should not have a noticeable impact on the outcomes of the scenario modelling exercises. The de facto starting point for interventions in Flanders is the presence of a largely depreciated natural gas network while at the same time DH networks are virtually non-existent.

For each intervention scenario the **total system cost or cost for society over the 30 year life cycle** will be considered; hence optimums are system or societal optimums.

In this way the resulting cost figures, even when expressed as a cost per household, also regard the total cost for society. We thus obtain a societal cost per household. This cost will often be different from the cost that is effectively paid by the individual building owner or household. For example, in the case of district heating provision, the investment costs for the district heating system are included in the 'cost per household' figures, whereas in practice these costs may only partially or indirectly be paid by the building owner. Resultantly, a given scenario may be profitable from the point of view of the individual building owner, but as certain costs have been shifted to other parties in the market, the aggregated figure may not be profitable. However, in a market situation, the district heating operator will depreciate the investment cost for the grid through the heating bills, thus shifting back these costs to the end user. In the present analysis, these forward and backward effects are neither modelled nor taken into account. They belong to the realm of business cases in a particular market set-up and are not the scope of this analysis. In more general terms, all types of optimized business cases and their related distribution of costs and benefits among the contributing parties (energy suppliers, grid operators, individual building owners, industries, local authorities, ...) are not studied.

For all the simulations a **discount rate of 3%** is applied but **no inflation rates or price evolutions** are modelled. This implies that neither (volatility prone) price evolutions of fossil fuels are taken into account, nor the decreasing investment costs of e.g. heat pumps or building envelope retrofit as their markets scale up.

In a similar vein the policy option of differentiating the price or tax (increase) rates for electricity and gas is not considered at this stage. However, price incentives shifting taxes from one energy carrier to another will strongly influence the optimal solutions. This type of intervention belongs to the policy domain and could, among others, be based on the results of the present study.

Finally, a concise set of **sensitivity analyses** is performed.

4.2. Sensitivity analyses

4.2.1 Connection rate and district variant

In the first sensitivity analysis, DH network connection rates are varied between **0, 50, 75 and 100%** and scenarios are shown for **all of the 9 districts** (3 central urban, 3 peri-urban and 3 suburban).

4.2.2. Cost of district heating source

The baseline analysis assumed a **low cost district heating source (13 €/MWh)**. In this sensitivity analysis the effect of **a medium or a high cost source is charted (32 or 42 €/MWh** respectively).

4.2.3. Fraction of retrofit cost accounted to energy-retrofit

Building envelope retrofit is an expensive intervention that however benefits both energy efficiency and other values like comfort; state of repair/condition of façade and roofs; aesthetic and real estate value. The base cases in the simulations therefore assign only **50% of the building envelope retrofit costs to the energy aspect sensu stricto. In order to assess the effects of this assumption**, a sensitivity analysis is performed where **100% of the building envelope retrofit costs are assigned to the energy aspect**. This allows to assess the effects on the total cost of ownership in particular (as energy and CO_2 figures will not be affected).

4.2.4. Discount rate

In all base case simulations a **discount rate of 3%** has been adopted. Discounting is an accepted economic method, but for long term societal challenges like climate change and the energy transition towards renewable, low carbon sources, it may be argued that future generations and thus future costs and benefits have an equal importance vis-à-vis the current generation.

For this reason a sensitivity analysis adopting a **discount rate of 0%** is performed.

5. Simulation results and interpretation

This result section is outlined in three main subsections.

Section 5.1 describes the **economic impact** of the different retrofit and district heating scenarios for **3 representative neighbourhoods** (one central urban, one peri-urban, one suburban).

Section 5.2 outlines the corresponding impact of the different scenarios on the **energy use and CO_2 emissions** for the different districts. The results in these 2 section are obtained for the following assumptions:

- a low-cost heat source is available to provide the required heat in the district heating network;
- only 50% of the total investment cost for building envelope retrofit is accounted for;
- when a district heating network is installed, all buildings connect to this network (100% connection rate);
- Districts 1 (Antwerpen-Berchem), 4 (Brugge St-Kruis) and 7 (Hasselt Kiewit) are representative for respectively the central urban, peri-urban and suburban district typologies.

In **section 5.3**, the **sensitivity** of the results to these assumptions is discussed.

5.1. Economic impact

5.1.1. Investment costs

Figure 3 shows the average investment cost per household as a function of the district scenario, respectively no district heating ('no DH'), 100% of buildings connected to a high-temperature district heating system ('100% HT') or to a low-temperature district heating system ('100% LT'). The subplots distinguish the type of district (urban, peri-urban, and suburban). The shape and colour of a data point depicts the renovation level of the buildings in the district.

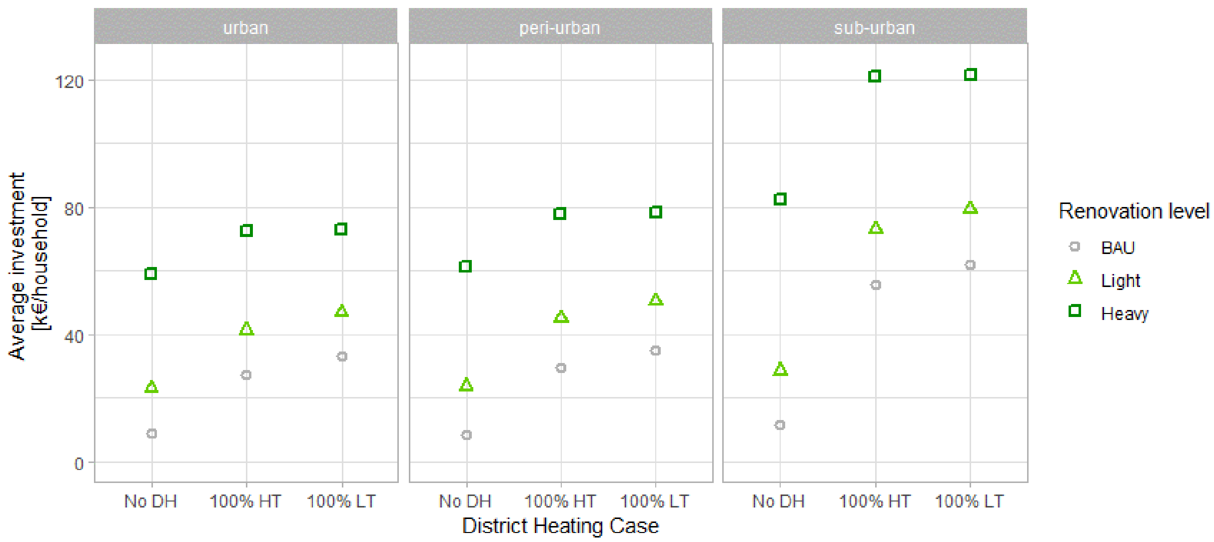


Figure 3: Average investment cost per household for a low-cost HT or LT DH source with 100% connection rate to the DH network, compared to no presence of a DH system; in all cases 50% attribution of the envelope retrofit cost to the energy related aspects.

- On average the investments for deep retrofit amount to 60-80k€ per household in urban areas, with higher, outlying values in the suburban regions as these are larger and mostly detached buildings in contrast to the terraced houses in the central urban and peri-urban districts. Light renovation typically amounts to 25-45k€, BAU to 10-30k€ (assuming 50% attribution of envelope retrofit cost).
- For the light renovation or BAU building scenarios, the average investment cost per household is higher for low-temperature networks compared to high temperature networks. The difference, about 5.000 €, is due to the need for booster heat pumps as these building scenarios do not allow for low-temperature heating.
- The relative increase of the total investment cost when installing a district heating network is higher for the suburban district, reflecting the longer distance covered by the network per household. Differences between the central urban and peri-urban districts are marginal. The sensitivity to these differences will be further discussed in 5.3.

5.1.2. Total cost of ownership

The total cost of ownership shows the discounted total investment and operational costs for the districts over a 30 year lifespan with a discount rate of 3%. It comprises investments for building renovations, gas/fuel and electricity costs for not-DH-connected buildings, investments in the district heating network, connection costs of buildings to the district heating network, and investment and operational costs of heat production in the district heating network.

Figure 4 shows the average total cost of ownership per household in function of the district scenario, respectively with no district heating ('no DH'), 100% of buildings connected to a high-temperature district heating system ('100% HT') or to a low-temperature district heating system ('100% LT'). As before, the subplots distinguish the type of district (central urban, peri-urban, and suburban). The shape and colour of a data point depicts the renovation level of the buildings in the district. Note that this figure only shows the results for the following assumptions:

- a low-cost heat source (e.g. incineration waste heat, (industrial) waste heat, specific green gas CHP applications) is available to provide the required heat in the district heating network;
- only 50% of the total investment cost for building envelope retrofit is accounted for;
- when a district heating network is installed, all buildings connect to this network (100% connection rate);

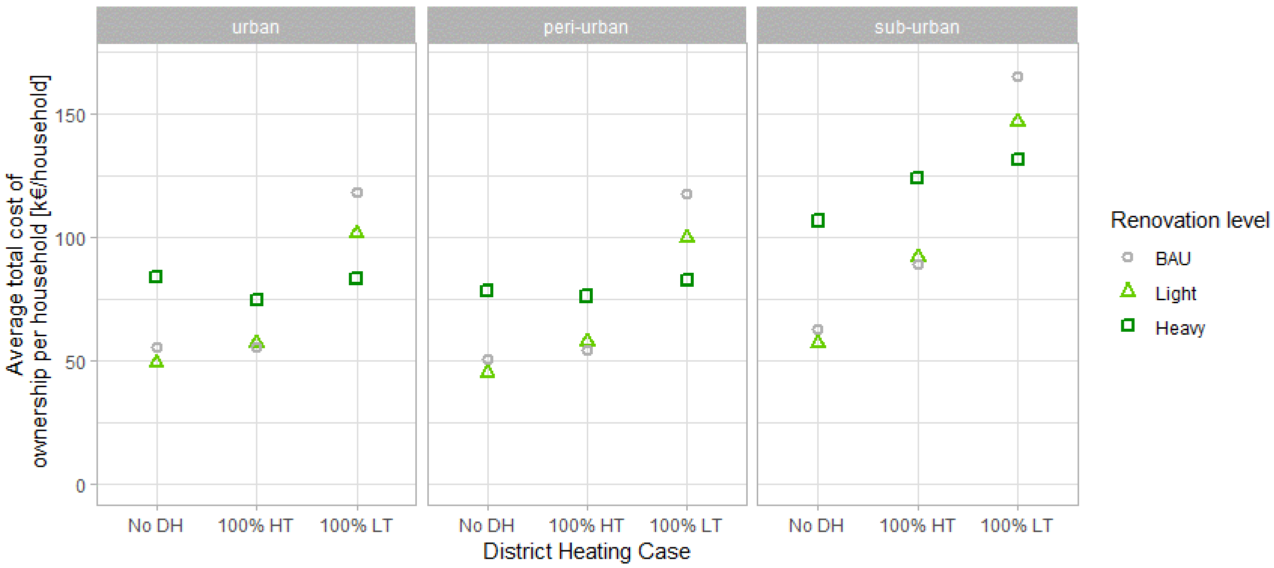


Figure 4: Average total cost of ownership per household (30 years horizon, 3% discount rate, 50% attribution of the envelope retrofit cost to the energy related aspects) for a low-cost HT or LT DH source with 100% connection rate to the DH network, compared to no presence of a DH system.

At current (fossil) energy prices, only performing a light retrofit and not rolling out any DH network is always the cheapest option, at least considered over a 30 year time horizon. BAU without DH comes at virtually the same cost. However, this approach does not help to realize any noticeable energy savings or carbon emission reductions.

Comparing the total cost of ownership of the district heating cases to that of the cases with no district heating gives insight into the profitability of a district heating system for the given district. Hence, Figure 4 shows how the profitability of district heating systems strongly depends on temperature level of the provided heat and the density of the heat demand (i.e. the urban density). When analysing the profitability of district heating, expressed as a lower total cost of ownership, two reference scenarios are of interest, being (1) a comparison against the BAU scenario without district heating and (2) the deep renovation scenario without district heating. The former is the BAU for the district whereas the latter exemplifies the 'all-electric' solution for mitigating 100% carbon emissions. Without district heating, these results show that on a 30 year period, the total cost of ownership (TCO) for the deep renovation scenarios is significantly higher than the BAU scenario. The high TCO for deep renovation can be explained primarily by the significantly higher investment cost (exterior wall insulation, window replacement, heat pump), but to a lesser extent also to the unfavourable ratio between the gas and electricity prices, which reduces the economic benefits of heat pumps.

In terms of urban density, the difference between central urban areas and peri-urban areas appears to be irrelevant for the studied cases: the internal differences within the groups are higher than the average differences between the two groups. Central urban areas have densities of about 40 to 70 households (or dwellings) per hectare; peri-urban areas have 30 to 60 households per hectare.

When low-cost and high-temperature heat is available in these central urban and peri-urban districts, the increase of total cost of ownership is negligible for the BAU and light renovation scenarios and even negative for the deep renovation scenario. The significant reduction in TCO for the deep renovation rate results from the fuel switching from the expensive electricity use of the heat pumps in the all-electric scenario, to the low-cost heat provided by the DH network (see also Figure 5). For the urban and peri-urban districts, this means that under the condition that carbon-neutral, low-cost, high-temperature heat is available, installing a district heating system is a cost-effective way of reducing greenhouse gas emissions. In that case and from a societal cost perspective, investments in building renovation should be kept limited. However, Figure 4 indicates that for the urban and peri-urban district even the combination of HT district heating and deep renovation have a slightly lower TCO compared to the all-electric scenario (i.e. deep renovation, no DH).

When district heating can only be provided at low-temperature, as can be expected for most 4th generation district heating systems, the high investment cost for the booster heat pumps and their high electricity use result in a significant increase of the TCO for the BAU and light renovation scenarios. Consequently, the TCO for these scenarios is higher than the all-electric renovation scenario (i.e. deep renovation, no DH).

When LT DH is combined with deep renovation, the total cost of ownership slightly increases compared to the HT scenario, due to the investment cost and electricity use of the booster heater for domestic hot water. Due to this increase and for urban areas, the total cost of ownership for deep renovation combined with low cost LT district heating is on a similar level as the stand-alone, all-electric solution. This conclusion is important when the aim is to realize carbon-neutrality. At the same time, a low cost LT heat source such as waste heat should be locally available over the long term to have such interesting DH case.

At the other end of the district typology spectrum, suburban areas stand out with substantially lower densities: about 10 households per hectare. Compared to the "all-electric" renovation scenario, Figure 4 shows that for the suburban district a district heating system is only a viable alternative if carbon-neutral, low-cost and high-temperature heat is available. Though, when buildings undergo deep renovation it is no longer profitable to still couple them to the district heating system as the TCO for the deep renovation case with HT is higher than the "all-electric" solution.

Figure 5 shows a breakdown of the total cost of ownership into its constituting parts:

- Investment in the DH network;
- Investment at the building side (retrofit cost + connection to DH + booster heaters in case of low temperature district heating);
- Maintenance cost for the district heating network (substations, heat source, back-up heaters);
- Cost for heating (gas/fuel or electricity for not-DH-connected buildings and heat cost + electricity use of booster heaters for buildings connected to the DH).

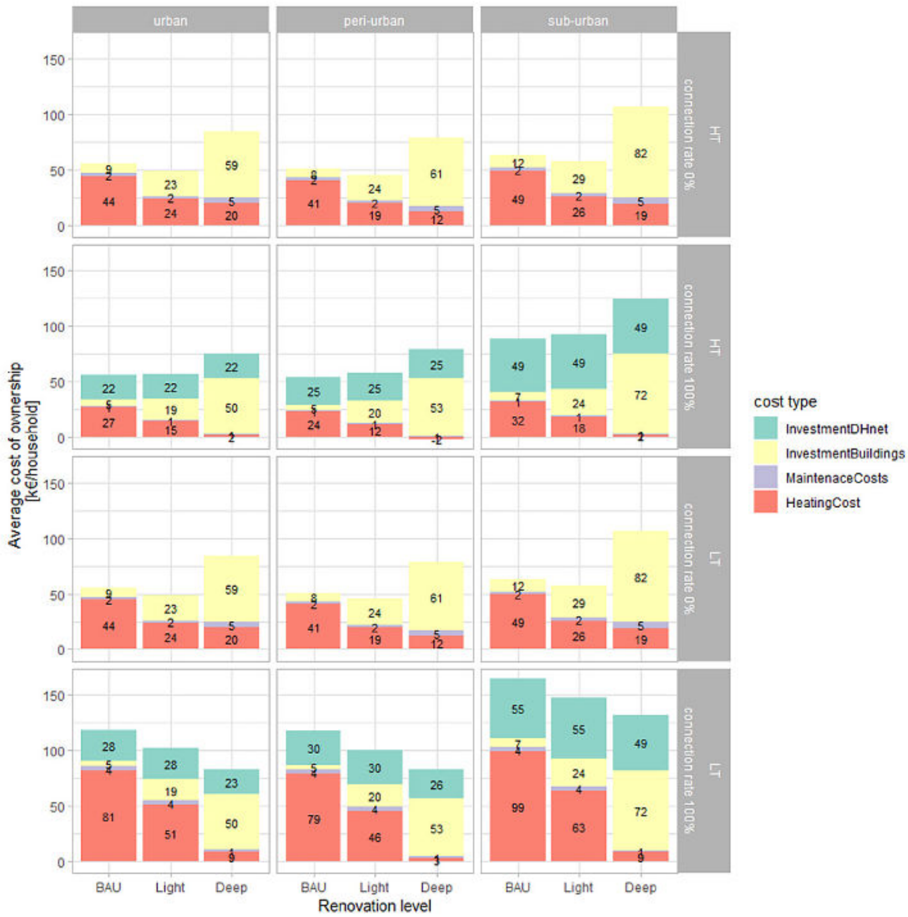


Figure 5: Breakdown of total cost of ownership among cost type (30 years horizon, 3% discount rate, 50% attribution of the envelope retrofit cost to the energy related aspects) for a low-cost HT or LT DH source with 100% connection rate to the DH network, compared to no presence of a DH system.

The breakdown of the total cost of ownership shows how for the low-temperature district heating scenarios, the high TCO for BAU and light renovation is mainly due to the high heating cost. This high heating cost results from the electricity use of the booster heat pumps that are needed as low-temperature heating is not directly possible, combined with the high remaining energy demand from the buildings as they were not or only lightly renovated.

5.2. Energy and CO_2 emission reductions

5.2.1. Relative annual energy savings

Figure 6 shows the relative energy savings as function of the district heating scenario. Energy savings are taken relative to the reference scenario being the BAU-renovation rate without district heating.

The subplots distinguish the type of district (central urban, peri-urban, and suburban). The colour and shape of a data point depict the renovation level of the buildings.

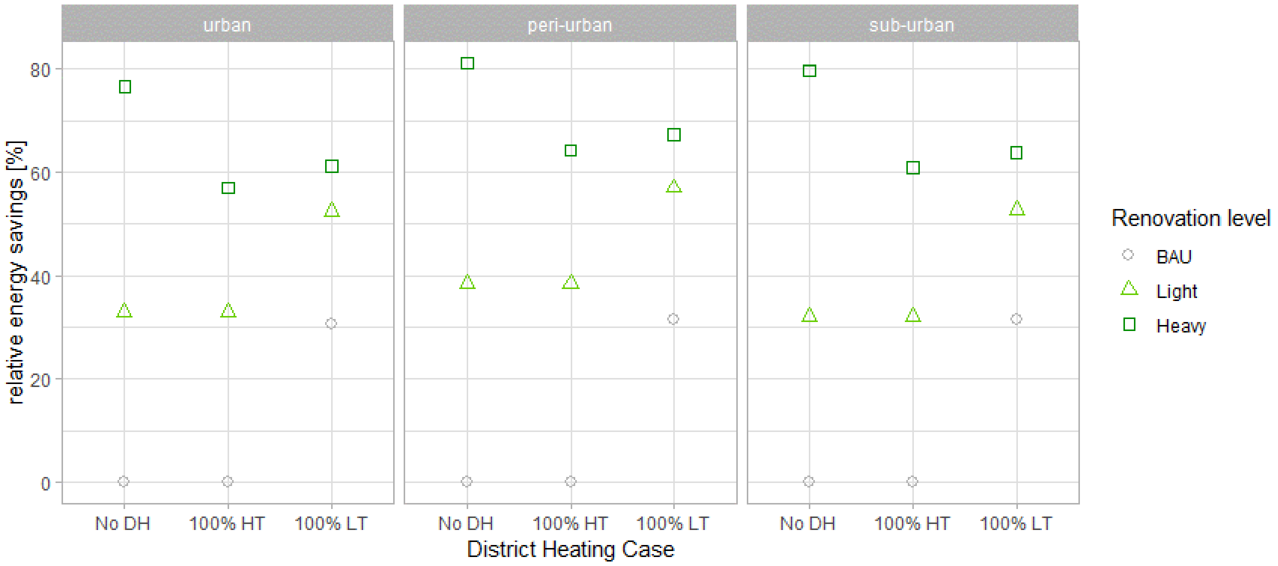


Figure 6: Relative energy savings as function of district and retrofit scenarios.

Without district heating, relative energy savings are about 30-40% for the light renovation scenario, and up to 80% for the deep renovation scenario. In all cases deep retrofit is the most energy saving option for obvious reasons. In practice these savings may be less extensive due to rebound effects. Analysis of the gas consumption data for these neighbourhoods showed that already today these buildings on average only have a gas use of 80-110 kWh/m². This is well below the typical values obtained in energy performance assessment of about 250 kWh/m², indicating that part of the investment in energy retrofit may also result in improved indoor comfort. In this study, no calibration of the energy use to gas consumption data (available at street level) is carried out, resulting in energy uses for heating and domestic hot water which are in line with the 250 kWh/m² value.

When buildings are connected to the high temperature district heating network no additional energy savings are obtained as only fuel switching occurs. Distribution losses in the district heating network have not been explicitly modelled. For the deeply renovated buildings energy savings decrease from 75-82% in the scenario without district heating to 55-65% when these buildings are connected to a high temperature district heating network, as the energy efficient heat pumps are replaced by the district heating connection. In fact, the ambient heat captured by the heat pumps is not counted as 'energy use', hence the better performance of the heat pump in deeply retrofitted buildings. As a result, the highest energy savings are always obtained by combining deep retrofit with the installation of a heat pump. Note that, in contrast to the general conclusion for DH networks, a (micro) DH grid based on heat pumps would deliver the same best performance.

When buildings are connected to the low-temperature network, significant energy savings are found for the BAU and light renovation scenario, since part of the heat is now delivered by the energy efficient booster heat pumps. Again, it is the incoming ambient heat share that improves the energy score.

As far as transport losses over the DH network are not taken into account, the DH scenarios display similar energy saving performances in urban and suburban neighbourhoods, but of course the investments to obtain these results remain much higher in the suburbs (see section 5.1).

5.2.2. Relative CO_2 emission reductions

Figure 7 shows the relative CO_2 emission reduction as function of the district heating scenario. The reference scenario is again the BAU-renovation rate without district heating. The subplots distinguish the type of district (central urban, peri-urban, and suburban). The colour and shape of a data point depict the renovation level of the buildings.

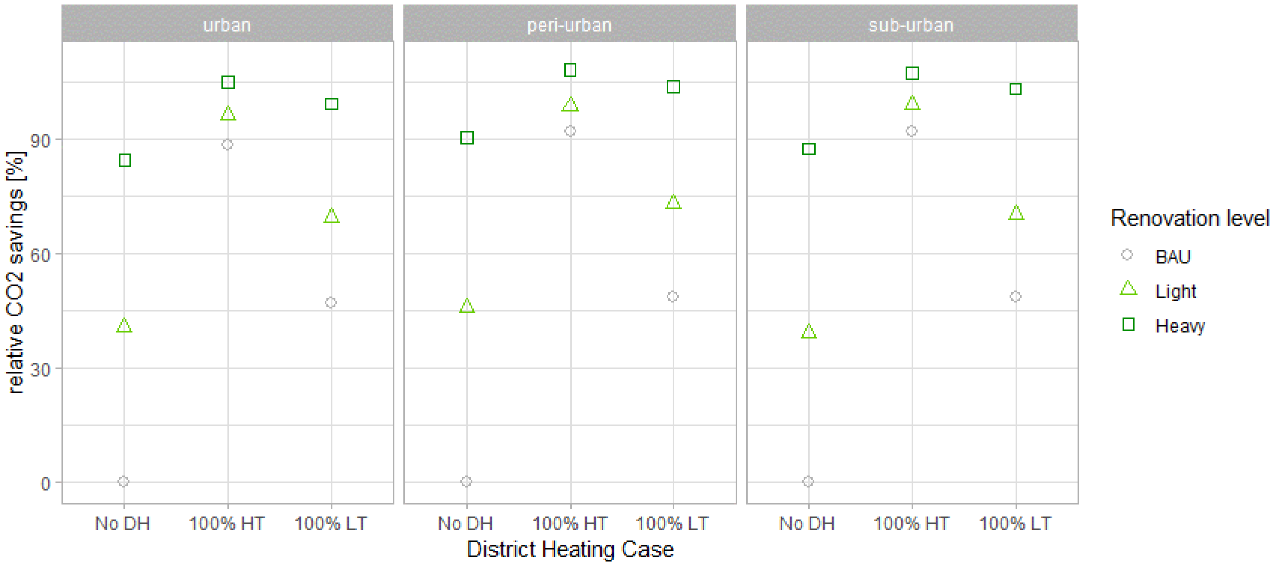


Figure 7: Relative CO_2 emission reductions as function of district and retrofit scenarios.

Under the assumption that the district heating system is supplied by a carbon-neutral heat source, a 100% CO_2 emission reduction for space heating and cooling is expected for all DH cases with 100% connection rate. Figure 7 shows that in case of connecting to the HT district heating, indeed 100% (or even 103%) CO_2 emissions reductions are obtained for the deep renovation scenarios, where PV systems are also installed in the renovation scenario to cover the domestic (not-heating related) electricity demand. In the case where savings are larger than 100% this PV was found slightly over-dimensioned. For the other cases, the domestic electricity demand is not (BAU) or only partially (Light renovation) covered, resulting in CO_2 emission reductions of 90% and 95% respectively.

When buildings are connected to the low temperature district heating network, CO_2 emission savings are significantly lower than for the HT district cases due to the use of grey electricity for the booster heaters. Note that the CO_2 intensity is assumed to be 285 g CO_2/kWh, which is in line with the EU-28 average in 2014[19]. Under the influence of climate action plans, this value can be expected to decrease until 2050. This evolution has however not been modelled explicitly. As a result of the decreasing carbon intensity, the differences between the HT and LT CO_2 emission savings are expected to decrease as the fall back on electricity would no longer be penalized. Following that reasoning, the relative CO_2 emission reductions for the all-electric solution (now 85%-90%) are also expected to increase to 100% when the electricity production is further decarbonized. The 100% target is not attained under the current assumptions as the sizing of the PV system is not covering both domestic electricity use and the electricity use of the heat pump system.

5.2.3. Total cost of CO_2 emission reductions

Figure 8 combines the results of the total cost of ownership with the results shown for CO_2 emission reductions. On the vertical axis the average total cost of ownership per household is shown indicating that the higher up the data point, the more expensive the scenario over a 30 year period. On the horizontal axis the relative CO2 emissions reductions are shown, placing more CO2 efficient scenarios to the right of the figure. The grey square on the left corresponds to the reference scenario, meaning that all data points located above the square on the vertical axis would be more expensive over a 30 year period.

The subplots distinguish the type of district (central urban, peri-urban, and suburban). The shape of a data point depicts the district heating case (no-DH, 100% low-temperature, 100% high-temperature), while the colour of the data point depicts the renovation level of the buildings. Again, these results are obtained under the assumption of a low-cost and carbon-neutral heat source for district heating and accounting only 50% of the investment cost for building envelope retrofit.

19 https://www.creg.be/sites/default/files/assets/Publications/Notes/Z1719NL.pdf

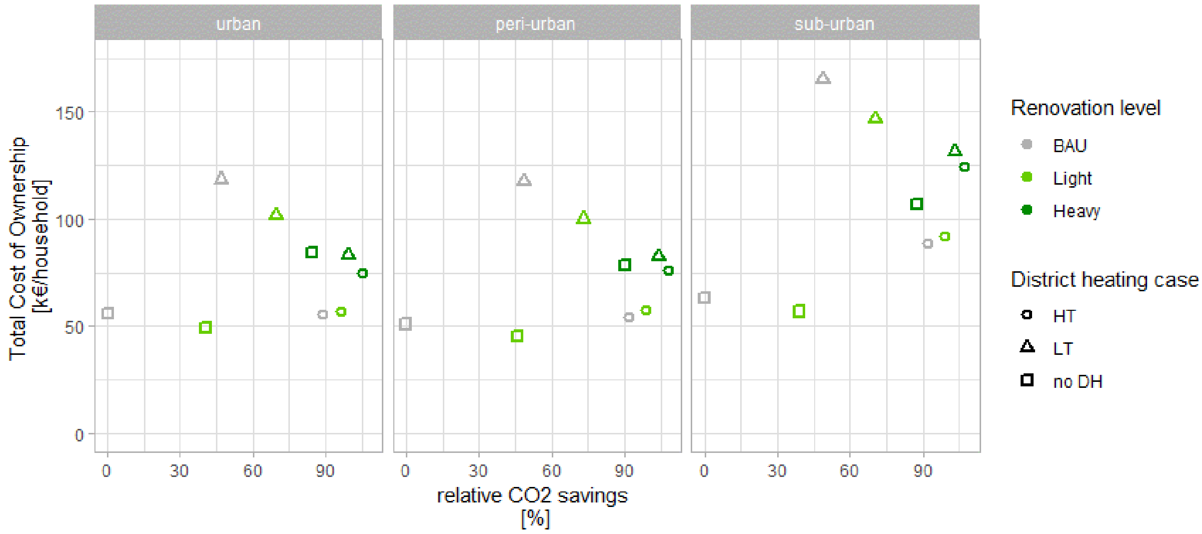


Figure 8: Total cost of ownership per household versus relative CO_2 emission savings as function of district and retrofit scenarios.

Figure 8 shows that central urban and peri-urban districts can be decarbonized (CO_2 emission reductions greater than 90%) at a total cost of ownership that is equal to that of the reference scenario when HT district heating networks can be applied. In that case, deep renovation would not be advised as this would increase the TCO by about 50%. Nonetheless, even when deeply renovated neighbourhoods would be able to connect to a high-temperature network (dark-green circle), the TCO of that solution would still be slightly lower than both the all-electric scenario (dark-green square) and the corresponding LT scenario (dark-green triangle). We must at the same time consider that sustainable HT sources may often display limited availability in the future, so it would from this point of view not be recommended to connect the deeply retrofitted neighbourhood to a HT DH network. As all-electric and connecting to a LT DH network come at comparable cost, this would often be the preferred options for deep urban and peri-urban retrofit.

Compared to the central urban and peri-urban districts, decarbonizing suburban districts is more cost intensive. When high-temperature heating is available, connecting buildings without deep renovation would be most cost effective (lowest TCO). However, the differences with the stand-alone, all-electric scenario are limited. Using low-temperature district heating is, under the given assumptions, always more expensive than the all-electric scenario for suburban districts.

Figure 9 represents these results by dividing the difference in total cost of ownership for a given scenario compared to the reference business as usual scenario by the reduction in CO_2 emissions over the 30 year period. The resulting number in euro per ton CO_2 can in this way be interpreted as the CO_2 abatement cost, meaning that mitigating 1 ton of CO_2 has cost that many euro[20].

The subplots distinguish the type of district (central urban, peri-urban, and suburban). The shape and colour of a data point depict the renovation level.

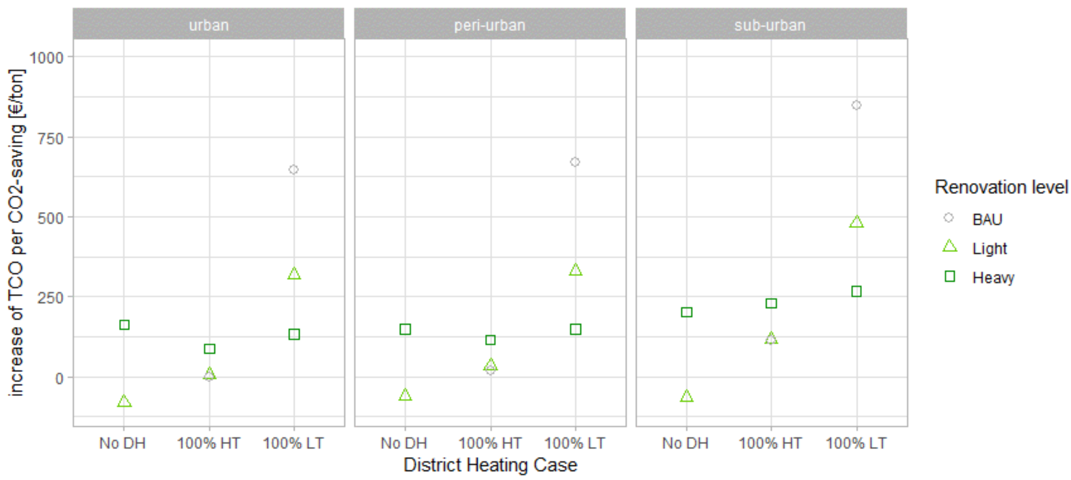


Figure 9: Marginal cost of ownership per ton of CO_2 savings as function of district and retrofit scenarios for a low-cost DH heat source and 50% attribution of investments in building envelope retrofit. Note that low cost heat sources include waste heat (both from industry and from waste incineration), but exclude biomass.

20 To put this into relief, it is interesting to compare the resulting figures with recent ETS carbon prices. For the latter, the range for the first half of 2019 was in the bandwith of 20 to 30 €/ton. Sources: https://sandbag.org.uk/carbon-price-viewer/, https://markets.businessinsider.com/commodities/co2-european-emission-allowances

Firstly, in all cases without district heating, negative values are obtained for light renovation, meaning that already today these options are more profitable than the BAU scenario (BAU without DH network is not in the graphs because it would yield a 0/0 score). For the all-electric scenario to become profitable, this figure indicates that a CO_2 price above 100-250 € would be needed, depending on the district type. This relatively high value can partially be attributed to the high electricity price. Under the given assumptions (low-cost, carbon-neutral heat source available and 50% building envelope retrofit cost attribution), this figure shows that for CO_2 prices of about 125 €/ton, a decarbonization solution can be found for all district types. When high-temperature district heating is available this is the most interesting solution for all district types and in central urban and peri-urban districts it even comes at a very low price. Otherwise, the differences between all-electric solutions and solutions based on low-temperature district heating are less significant since heavy retrofit is also needed to optimally benefit from a low-temperature district heating system. If a low-temperature district heating system is profitable in those cases depends on the district type. BAU combined with LT DH connections is excessively expensive, due to the remaining high energy demand and the reliance on a booster heat pump to fill in this demand. Light retrofit reflects the same situation to a lesser degree, as the energy demand has been slightly reduced.

5.3. Sensitivity analysis

5.3.1. Sensitivity to connection rate and district variant

In the results of section 5.2, a 100% connection rate to the district heating was assumed when the latter was present. When district heating is implemented in existing districts and unless legal measures are taken, it is expected that not all buildings will connect. Therefore, this section discusses the sensitivity of the investment costs and TCO to these connection rates. Four connection rates are being considered: 0% (no DH), 50%, 75% and 100%. Rolling out a DH network at a 25% connection rate makes little sense from the efficiency point of view.

At the same time the analysis is extended to the 9 case study districts, in order to observe the internal differences between each of the 3 central urban, peri-urban and suburban neighbourhood types.

Figure 10 shows the average investment cost per household as function of the connection rate for the district heating network. In the horizontal direction, the subplots distinguish the type of district (central urban, peri-urban, and suburban). In the vertical direction, the subplots show different instances of those district types, each time for the low-temperature (LT) or high-temperature (HT) case. For connections rates below 100% different combinations of renovation levels have been applied to buildings connected to the district heating on the one hand, and those that are not connected to the district heating on the other hand. Therefore in Figure 10, the shape of the data point depicts the renovation level of the buildings connected to the grid, while the colour of the data point depicts the renovation level of the buildings that are not connected to the grid.

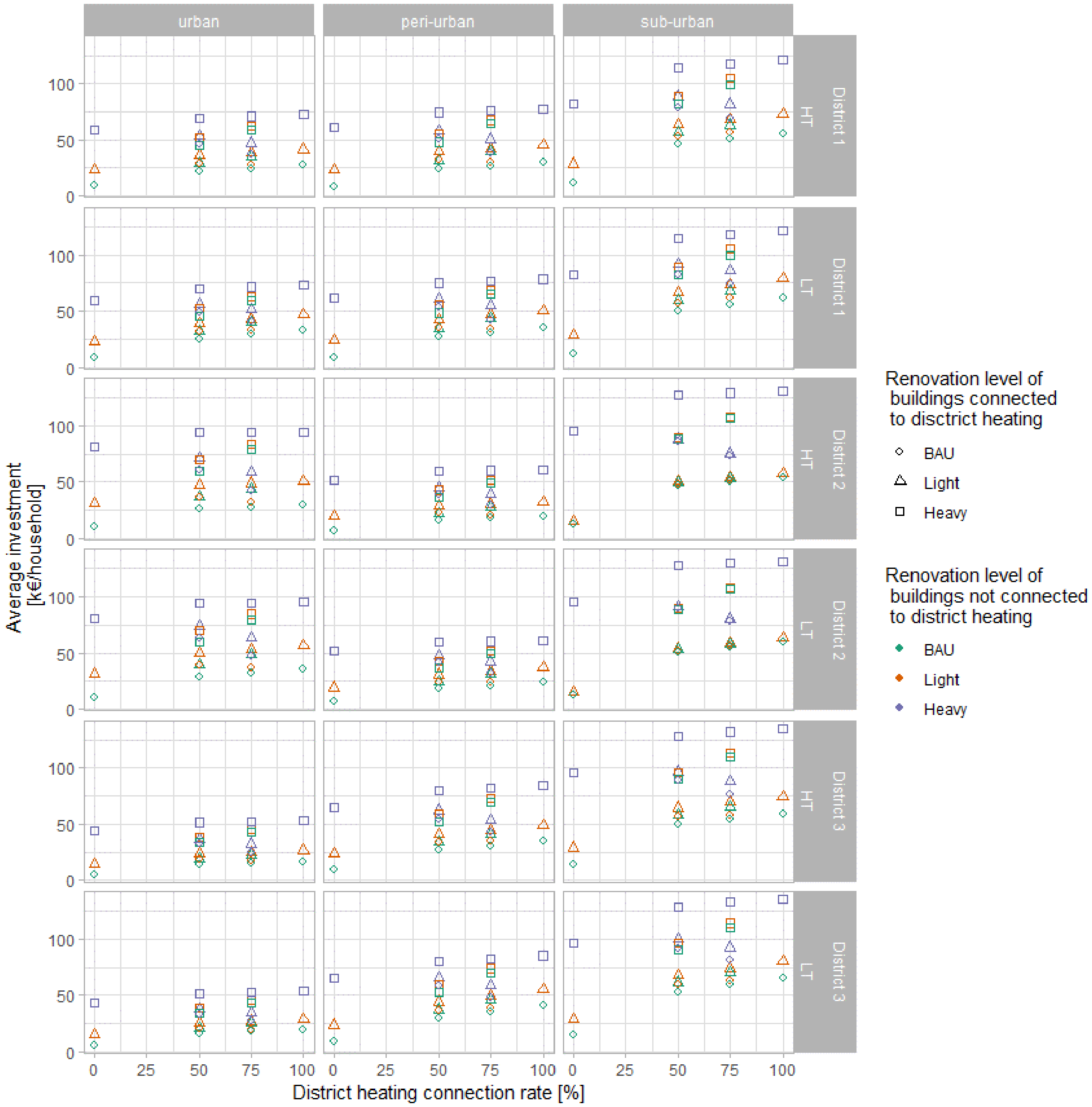


Figure 10: Sensitivity of average investment cost per household for a low-cost DH source and 50% attribution of investments in envelope retrofit, to the connection rate and district variants.

As expected, these investment costs fall between the extreme solutions (0% and 100% connection rates) discussed in section 5.2, even if retrofit levels are being differentiated between connected and non-connected buildings. More interesting is however the impact on the TCO shown in Figure 11.

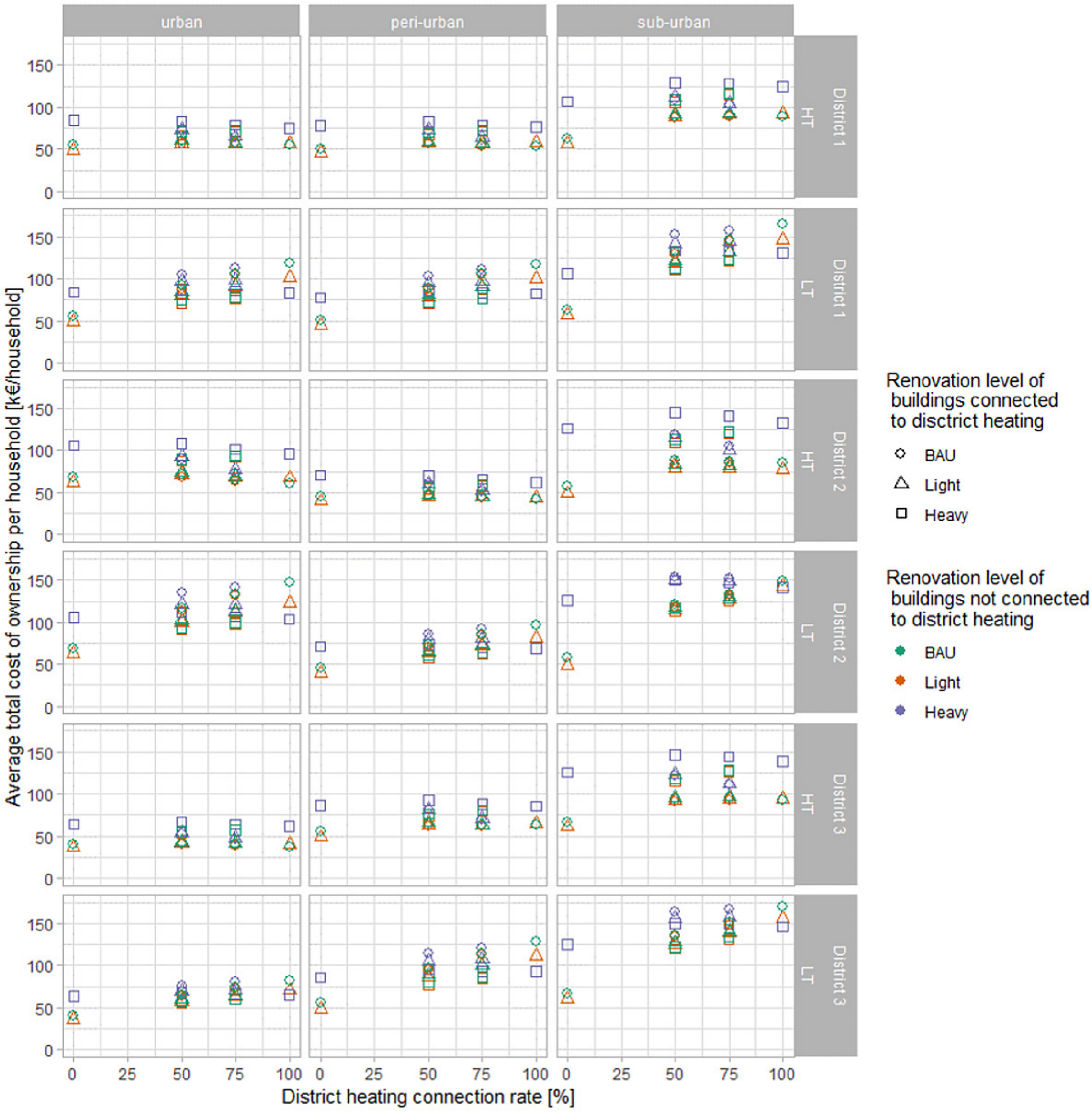


Figure 11: Sensitivity of the average total cost of ownership per household (30 years, 3% discount rate) for a low-cost DH source and 50% attribution of investments in envelope retrofit, to the connection rate and district variants.

General tendencies

For HT DH cases, the TCO only slightly increases with decreasing connection rates. The business cases are thus not fundamentally altering between a 50% and 100% connection rate. Once the DH network has been rolled out, the advantage of connecting more homes exists but is limited, at least from the point of view of the TCO for society. In urban areas, stand-alone, all-electric deep retrofit always remains more expensive except where buildings are systematically deeply retrofitted and at the same time only for 50% connected to the DH system: this scenario is clearly a waste of means by sub-optimally introducing a 'double' solution.

For LT DH cases, the TCO increases with increasing connection rates, especially where expensive booster heat pumps are needed for the BAU or lightly retrofitted buildings. The contra-intuitive conclusion that more connections bring on a worse business case, is fully due to the situation that staying with a stand-alone, fossil fuelled home is cheaper than connecting it to a DH system for which it is not prepared. Together with the high electricity price, this leads to a financial punishment for connecting to the DH network.

Detailed analysis

As for the base cases, light retrofit without rolling out a DH network comes forward as the cheapest option, at least for current fossil fuel prices and based on a 30 year investment horizon. BAU without DH remains close. For obvious reasons, a partial connection rate to the DH network does not alter this situation. But neither does the district type or case. Only some urban HT DH scenarios can compete, but only as far as no buildings are deeply retrofitted at the same time.

Any combinations with deep retrofit (purple and/or square plots), even if building envelope measures are only accounted at 50%, generally remain in the higher cost range for a given district.

This already leads to the conclusion that without any tax or price incentives, low carbon solutions will rarely develop on a single basis of cost effectivity. Only cheap, carbon-free HT DH may be competitive in certain urban areas. In the latter case, the district may thus become carbon-neutral but will at the same time continue to consume considerable amounts of energy.

For the high-temperature district heating cases, Figure 11 shows that connecting all buildings to the district heating network results in a lower TCO than the partial connection scenarios. For these high-temperature district heating scenarios, the preferred combination of building renovation measures is generally the same for all connection rates, with light renovation having a similar or slightly lower TCO compared to BAU and a significantly lower TCO comparted to deep retrofit, considered over 30 years.

Note that scenarios in which buildings not connected to the DH do not undergo deep retrofit, only partially result in a decarbonized district. When aiming at carbon neutrality, buildings should either be deeply retrofitted or be connected to a carbon-free DH network (with varying degrees of retrofit possible for the connected buildings).

With carbon-free functioning as a goal, we observe that the stand-alone all-electric scenario is rarely giving a lower TCO than most of the HT DH scenarios in urban areas, whatever the connection rate. In suburban areas the HT DH scenarios can compete with stand-alone all-electric if the buildings are not deeply retrofitted, and this again rather independently from the connection rate. However, all scenarios involving substantial DH connection rates and no or light retrofit for the connected buildings, will be battered by high energy demands even if this energy demand has been decarbonized. The question will then rather be if that quantity of sustainable energy is locally available at all.

With carbon-free HT DH possible at low heat production costs, the case for doing nothing or hardly anything (i.e. not installing the DH network and performing no or only light retrofit to buildings) is weak: rolling out and connecting to the DH network is only a bit more expensive, but will greatly save on CO_2-emissions.

For the low-temperature DH scenarios a different image appears. The total cost of ownership on average keeps increasing for higher connection rates. Given the high investment and operational costs of coupling buildings that do not allow low-temperature heating to low-temperature district heating, Figure 11 shows that in all cases the buildings connected to the low temperature DH preferably undergo deep retrofit. Buildings not connected best undergo light or BAU renovations from an economic perspective. It should however be noted again that with the latter option taken, a full decarbonization is not attained.

In suburban areas and while aiming at carbon-free functioning (this implies that all non-connected buildings are deeply retrofit by definition), it makes little sense to roll out LT DH: the stand alone all-electric option is cheaper in all cases. Note that the stand-alone all-electric scenario implies deep retrofit of all the buildings was well. In other words, rolling out a LT DH network for only part of the dwellings and having these dwellings install a booster heat pump rather than deeply retrofitting them, makes no sense.

In all scenarios, we observe that the internal differences between different urban or peri-urban districts may be more important than the differences between urban and peri-urban districts as distinct neighbourhood categories. This is logical as urban densities for the considered central urban areas vary from 40 to 70 households/ha while the peri-urban areas have 30 to 60 households/ha, resulting in substantial overlap between the two categories. Therefore, we can conclude that making a difference between urban and peri-urban contexts results to be needless.

However we systematically observe different outcomes for suburban areas (average urban density 10 households/ha). This means that urban density greatly matters, in particular when aiming at carbon-free functioning.

To clarify the trade-off between TCO and CO_2 savings, Figure 12 finally recapitulates Figure 8, again while adding the dimension of the connection rate (this time shown by the increasing size of the data point) and extending the scope to the 9 case study districts.

Where decarbonization (more than 90% CO_2 savings) is the ambition, in all districts a 100% connection to a high-temperature district heating network is the most cost effective solution (lowest TCO). When only low-temperature district heating is available buildings should always undergo deep retrofit. In those cases, a district heating system can still be profitable for central urban and peri-urban districts, while for the suburban districts the all-electric solution (no DH) generally results in a lower TCO.

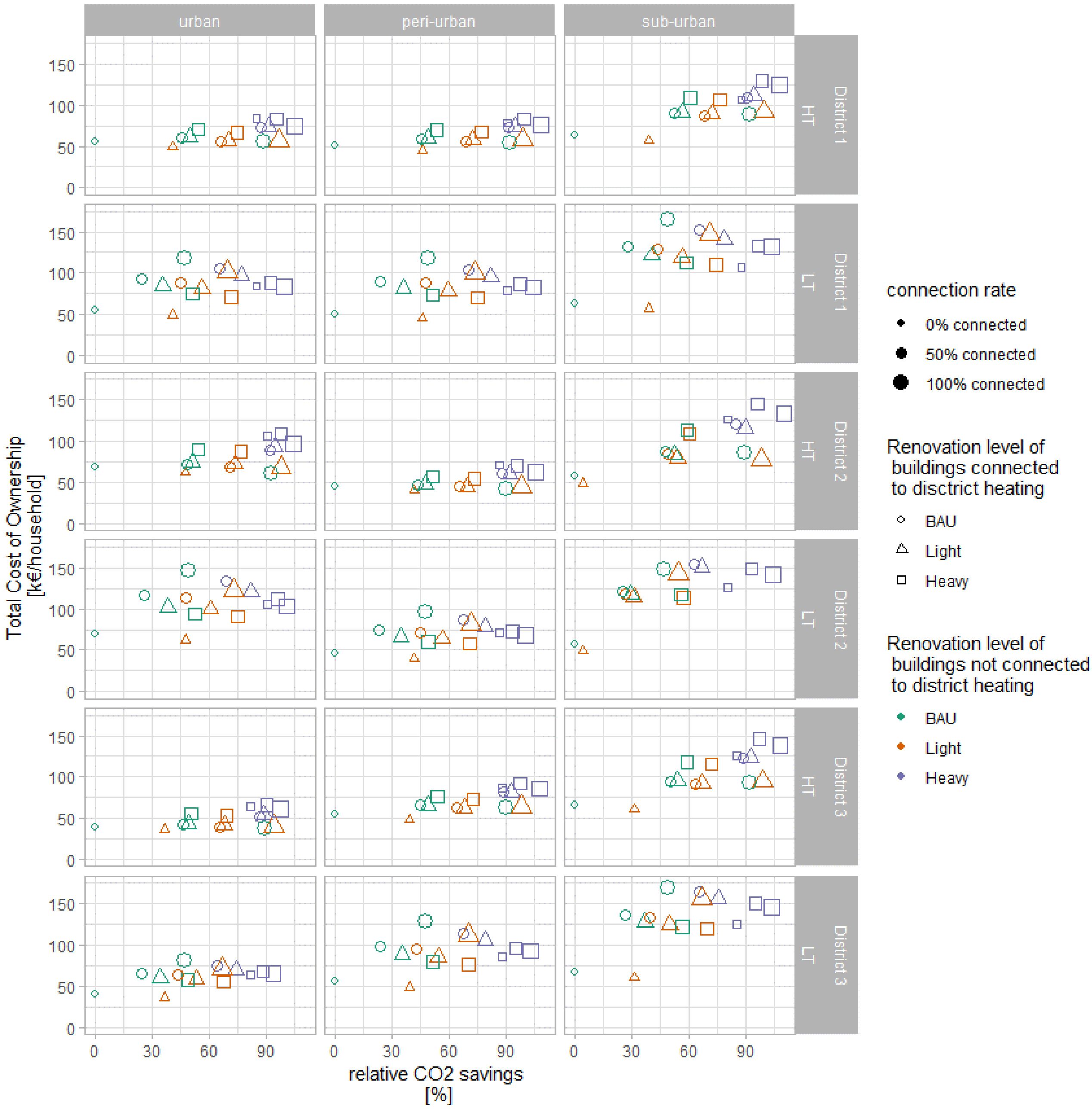


Figure 12 Total cost of ownership per household versus relative CO_2 emission savings as function of district and retrofit scenarios, for a low-cost DH source and 50% attribution of investments in envelope retrofit.

5.3.2. Sensitivity to cost of district heating source

Figure 13 below shows the impact of the cost of heat production in the district heating network on the total cost of ownership for a 100% connection rate. Heat prices vary from 12.8 €/MWh for low-price over 32.5 €/MWh for mid-price to 42.9 €/MWh for high price scenarios. The results are only shown for the first district variant to improve readability.

Figure 13: Sensitivity of total cost of ownership to price scenario for district heating source, 100% connection rate, assuming 50% of building envelope retrofit costs are attributed to the energy aspect. 'no DH' depicts the scenario without district heating as a point of reference.

We observe a (very) moderate influence. This tendency is, obviously, more outspoken in cases of no or light retrofit combined with a DH connection, as these scenarios have the higher energy demands from the DH grid. In other words, higher DH heat production costs are mainly detrimental to districts with buildings that have poorer insulation standards.

Heat production costs may become a decisive factor where the feasibility of a DHC network is at the limit.

Compared to the situation where no DH network is present, the conclusions do not fundamentally alter.

5.3.3. Sensitivity to fraction of retrofit cost accounted to energy-retrofit

Figure 14 and Figure 15 below show the average cost of ownership under the assumption that the full retrofit cost is attributed to energy-retrofit. Note that for the other sections it is assumed that only 50% of the retrofit cost of the building envelope needs to be attributed to energy-retrofit while the remaining 50% is accounted to the increase in real estate value, comfort and living quality for the home owners.

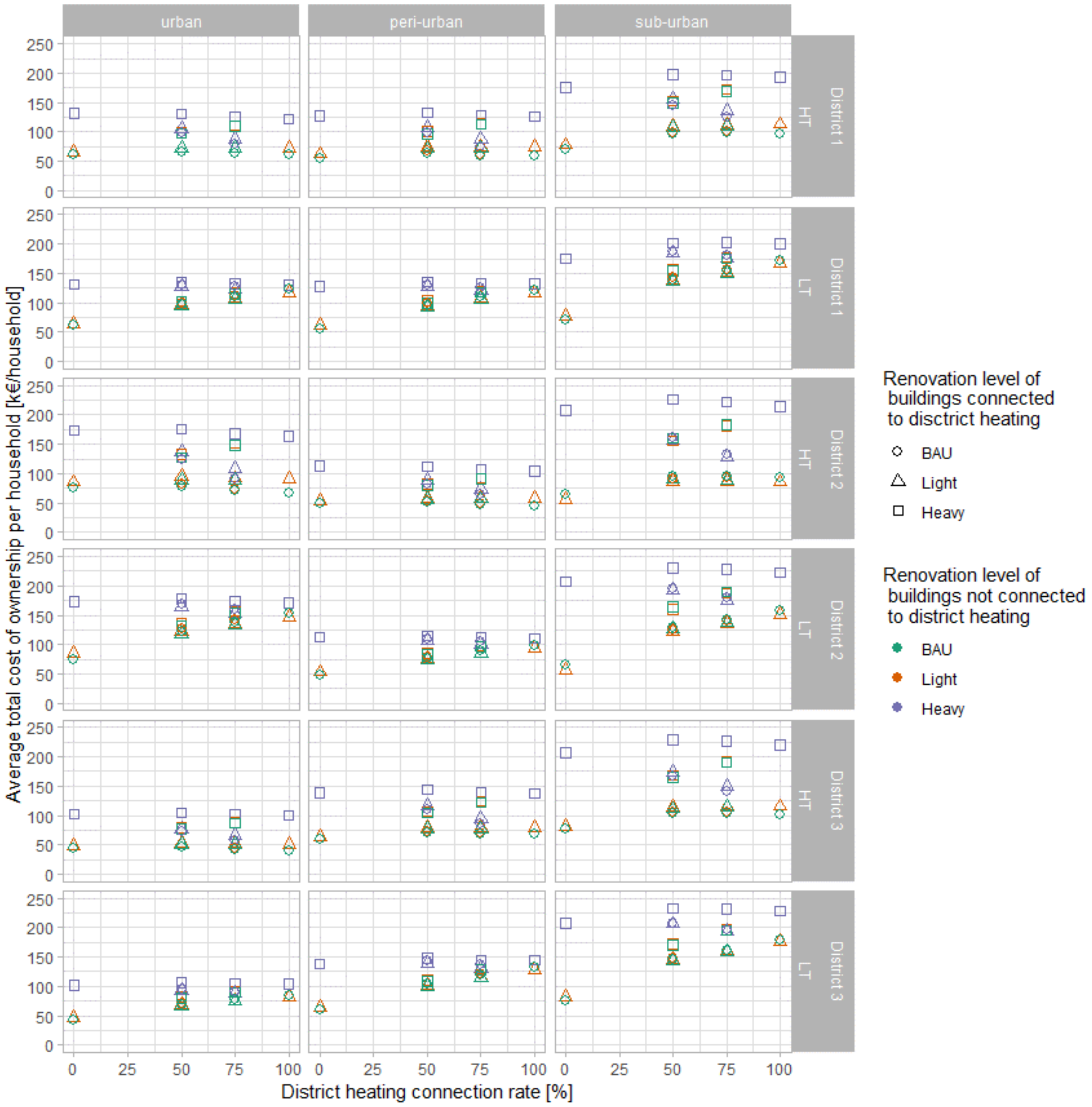
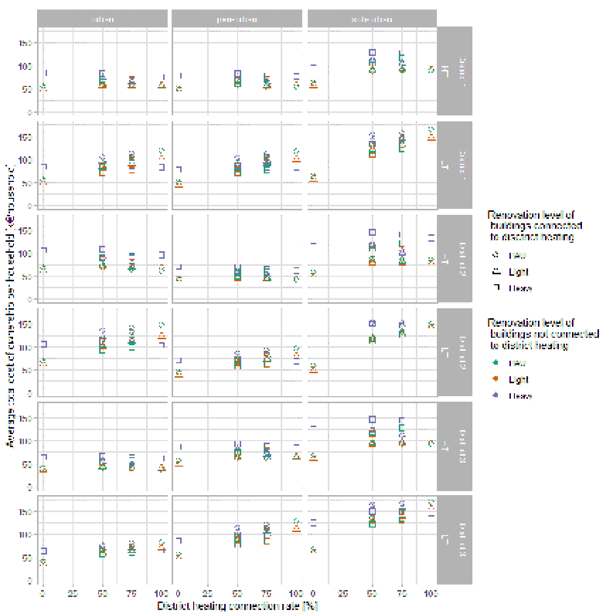


Figure 14: Average total cost of ownership per household (30 years, 3% discount rate) for a low-cost DH source and 100% attribution of investment in envelope retrofit. This graph must be compared to Figure 11, which is copied below.



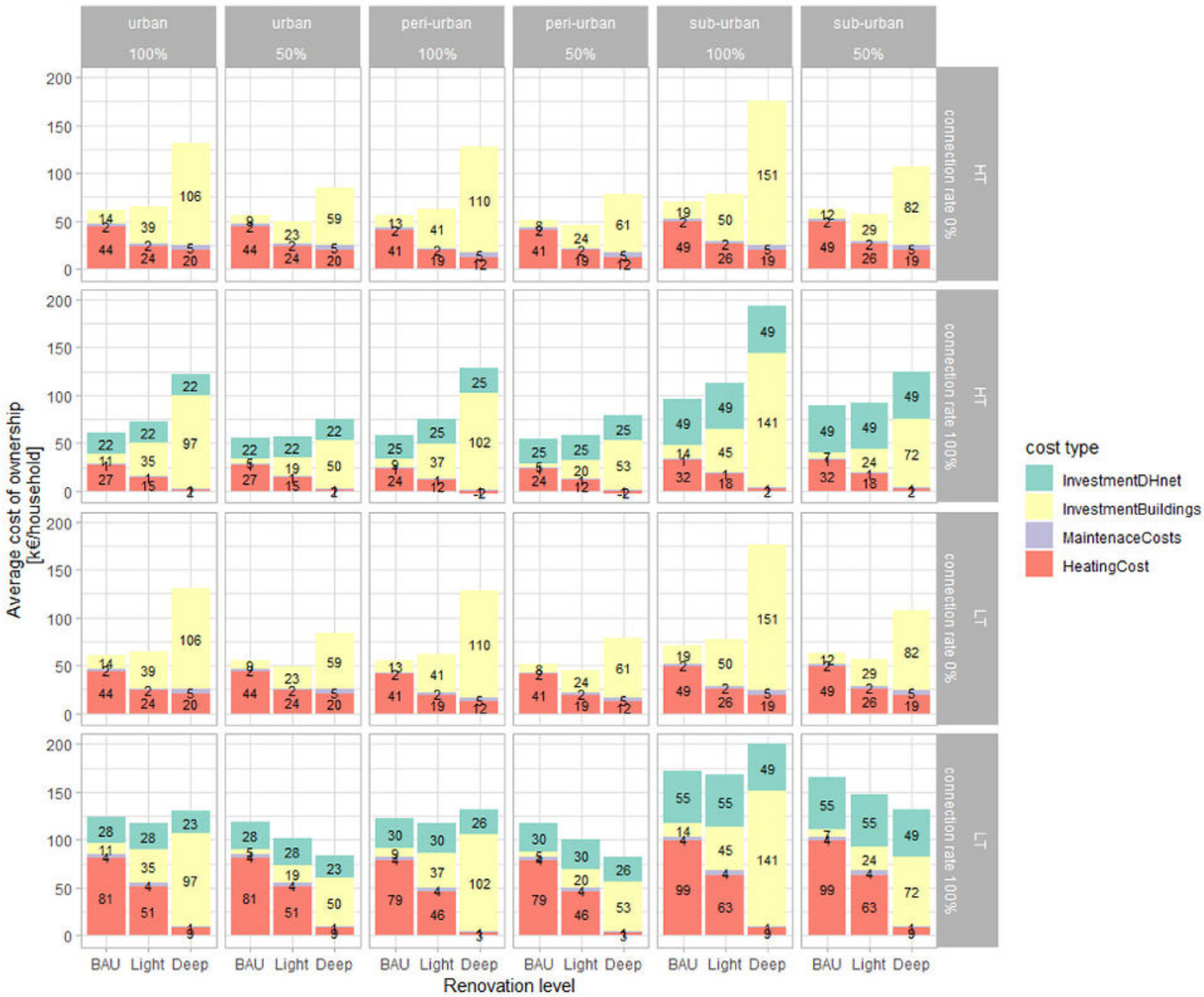


Figure 15: Comparison of average total cost of ownership breakdown when attributing 100% or 50% of the envelope retrofit investment costs to energy-retrofit (30 years, 3% discount rate, low-cost DH source).

Firstly, Figure 15 clarifies the strong sensitivity of the assumption towards retrofit costs on the total cost of ownership. Especially for the deep renovation scenario, investment costs in buildings by far exceed the total heating cost when all investments are attributed to energy savings. Consequently, Figure 14 shows that the difference in total cost of ownership between the all-electric solution (0% connection) and the 100% HT DH connection with BAU or light renovation has significantly increased. In other words, under those assumptions that low-cost, carbon-neutral and high-temperature heat is available, 100% connection BAU renovations are the preferred scenario to decarbonize districts. Note that when only 50% was accounted for, light renovation had a slightly lower TCO than BAU, this is no longer the case when renovations are accounted at full-cost.

As a result of the strong increase of investment costs in deep retrofit compared to the cost of booster heat pumps, also for the low-temperature network, deep renovation is no longer the preferred option in any of the districts. Especially for suburban districts, the TCO of 100% connection and deep renovation is now significantly higher than for the BAU and light renovation measures. In the central urban and peri-urban districts differences are less significant.

5.3.4. Impact of discount rate on total cost of ownership

The discount rate can be brought to 0% to assess the effect of not discounting, i.e. putting future value at exactly the same level of appreciation as present value.

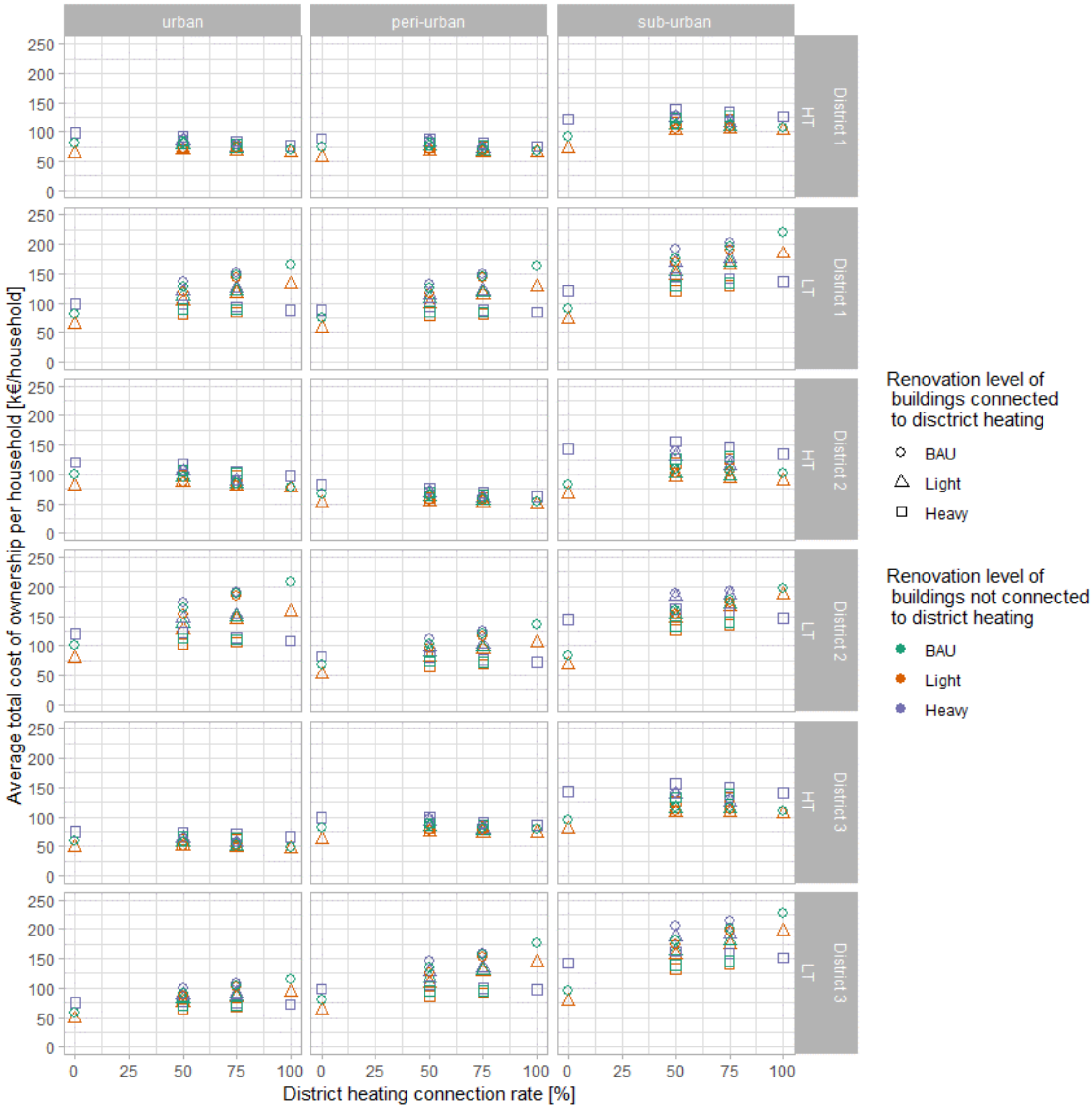
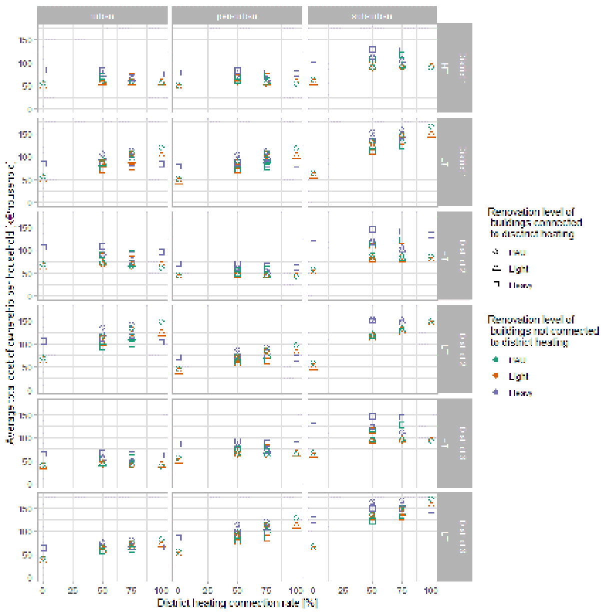


Figure 16: Average total cost of ownership per household (30 years, 0% discount rate) for low-cost DH source and 50% attribution of investment in envelope retrofit. This graph must be compared to Figure 11, which is copied below.



The TCO for BAU and light retrofit scenarios increases significantly and deep retrofit becomes more attractive or even competitive in scenarios where it formerly was not, because future heating costs are now given an equal weight as present heating costs.

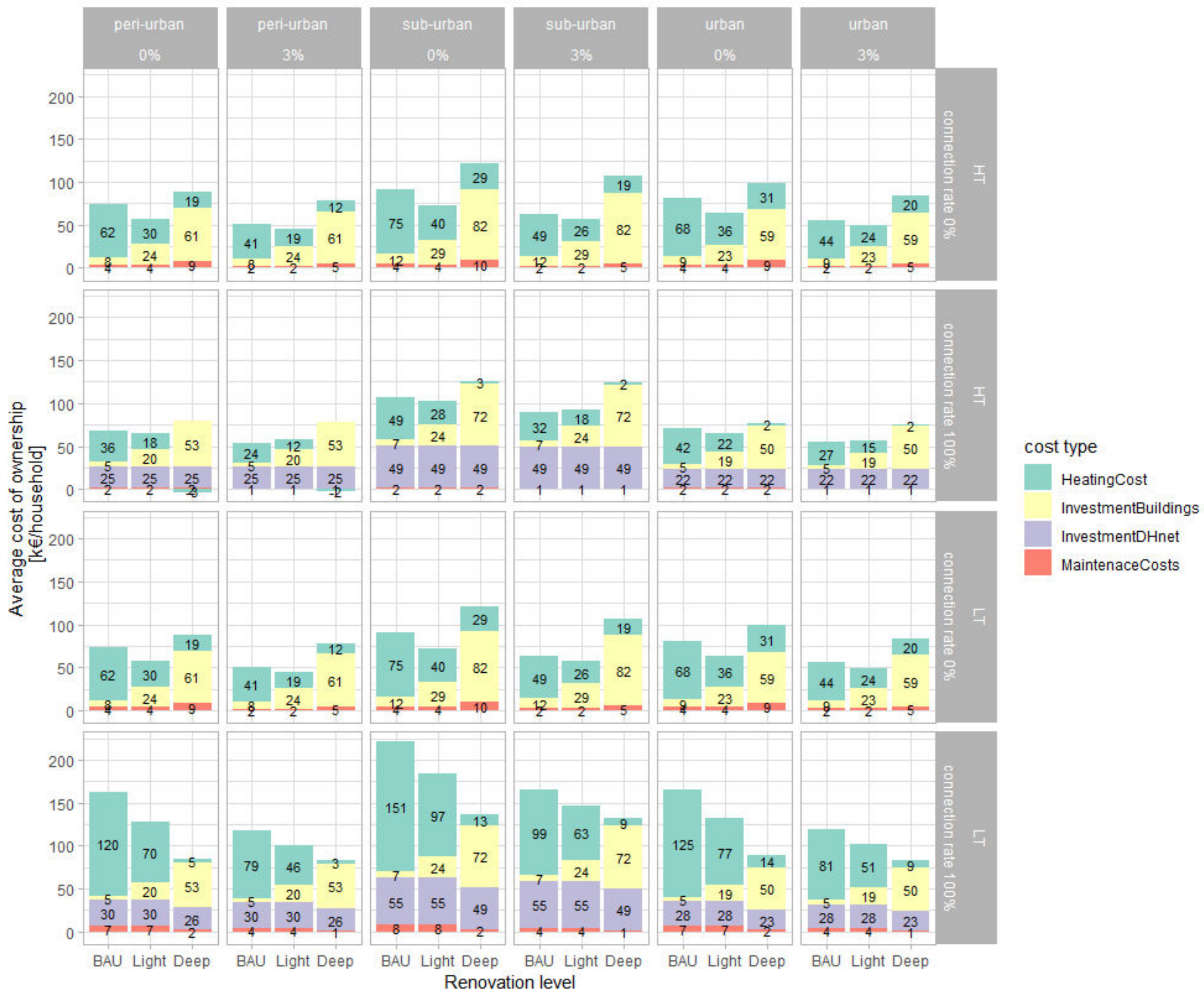


Figure 17: Comparison of average total cost of ownership breakdown for 0% and 3% discount rate respectively and attributing 50% of the envelope retrofit investment costs to energy-retrofit.

5.3.5. The role of urban density

The profitability of district heating systems strongly depends on the spatial density of the heat demand, and hence on the urban density.

In terms of urban density, the difference between urban areas and peri-urban areas appears to be irrelevant for the studied cases: the internal differences within the groups are higher than the average differences between the two groups. Central urban areas have densities of about 40 to 70 households (or dwellings) per hectare; peri-urban areas have 30 to 60 households per hectare.

Suburban areas however stand out with substantially lower densities: about 10 households per hectare.

Therefore, it is relevant to observe two categories, urban and suburban districts. The internal variation of densities is substantial in urban contexts (up to more than a factor 2); in suburban contexts it is virtually non-existent. In the outputs the difference between these two categories become obvious throughout all of the scenarios. Often, solutions fit for urban situations are not appropriate for suburban locations.

6. Conclusions

The present study analyses the trade-off between increasing energy efficiency (EE) of the building stock on the one hand and supplying it with renewable energy (RE) and/or sustainable district heating (4G) on the other hand. Different scenarios are compared in terms of energy use, carbon emissions and cost. Simulations have been run based on a Python algorithm (EBECS with extensions) for 9 selected urban districts in Flanders: 3 central urban neighbourhoods, 3 peri-urban districts and 3 suburbs. This allows to account of urban density as an important variable.

More in particular the following influencing factors and variables have been considered, apart from the building characteristics that were determined for the 9 urban districts, both through visual and statistical assessments:

- The level of building retrofit to be applied: BAU, light retrofit or deep retrofit;
- The attribution of the building envelope retrofit costs to the energy aspect: 50% or 100%;
- The type of heat provision: no DH, HT DH, LT DH;
- The cost of the DH source: low cost, medium cost or high cost (13, 32 or 42 €/MWh respectively);
- The degree of connection to a DH network when it is present: 50%, 75% or 100%;
- The urban district type: central urban, peri-urban (together labelled as 'urban') and suburban;
- The discount rate: 3% or 0%

From a multitude of possible development combinations, only scenarios that are technically feasible have been selected. For example, when a district is set to be served by low temperature district heating while the buildings have only been lightly retrofitted, booster heat pumps are foreseen in order to upgrade the incoming low temperature heat towards a level that is suitable for the buildings in case.

In this way a broad scala of choices could be mapped, going from the simplest BAU - only doing regular repair of buildings and not rolling out any district heating networks - to 'all-in' retrofit scenarios that combine deep building retrofit and renewable energy production with provision of sustainable heat via a DH network. The starting situation is one where natural gas networks are already present and have been (largely) depreciated, while DH networks are absent. This puts natural gas networked solutions at a competitive advantage, but this is also the situation on the ground in large parts of Flanders – particularly in the urbanized areas which are the focus of this study.

The goals to be reached can be a combination of energy savings, carbon emission reductions and the lowest total cost of ownership from a societal perspective. **With a view on the EU energy and climate targets, it is in particular interesting to investigate how high emission reductions can be achieved while at the same time minimizing the total cost of ownership.** It is interesting to know how much low carbon scenarios cost, compared to business as usual – assuming that fossil fuels remain available at the price levels of today.

Standard assumptions were an investment horizon of 30 years, a 3% discount rate and 50% assignment of building envelope retrofit costs to the energy aspect, given that retrofitting the building envelope also increases comfort, the state of repair of façades and roofs, the aesthetics and the real estate value. In this way retrofitting a building shall not only be considered as an energy investment.

Sensitivity analyses were performed to assess the effect of these and other assumptions.

The results of the simulations lead to the following conclusions:

Carbon lock-in

Without any tax or price incentives (including market price increases for fossil fuels), low carbon solutions will rarely be developed on the single basis of cost effectivity. Compared to BAU or light retrofit scenarios where no DH networks are being rolled out, only low cost HT DH network solutions may be competitive, and this only in certain urban areas. In the latter case, the district may thus become carbon-neutral if the DH source is carbon-free, but it will at the same time continue to consume considerable amounts of energy. This implies that at current price levels for fossil fuels and with present tax distribution shares over electricity versus gas and heating fuel, there remains a deep societal lock-in for energy and carbon intensive functioning.

When explicit carbon emission reduction goals are set as a boundary condition, the picture changes substantially and shows a diversified palette of possible EE-RE-4G combinations coming forward as feasible solutions. Hereby there appears to be no basic rule like 'always perform deep retrofit' or 'always roll out DH networks in urban areas'. Temperature level and cost of the DH source, as well as urban density, play an important role for distinguishing the options with the lowest TCO.

Where energy savings are targeted, it is obvious that only increasing EE brings real relief and hence deep retrofit of the building stock will be the best option – coming at a high cost however. In a second order, heat pumps may deliver additional EE as they rely only partially on accounted energy (the needed electricity) and for the rest utilize (unaccounted and for free) environmental heat. However, in order to be effective, these heat pumps need to operate in a context of low energy demand.

A general and major barrier for intervention is the high cost of building retrofit.

Energy savings may however be an important parameter for solving the regional 'energy puzzle', see below, and thus be necessary in any case.

Further research is needed to understand the widespread occurrence of low measured energy consumption figures in the sample districts, even remaining below the 100 kWh/m² annual limit for space conditioning in the actual situation. It may be suspected that factors such as prebound and energy poverty play a role. Low actual energy consumption figures jeopardize the business case for retrofit in terms of potential financial savings and the related payback periods of EE measures, but do not change the case for improved comfort and better preparedness for a low carbon future.

Options for a low carbon future

If the intention is to avoid deep and expensive retrofit of the building stock while still realizing low carbon goals, the challenge is in providing sufficient amounts of sustainable or renewable energy for such approach. There are 3 possible scenarios (Figure 18):

- Stand alone: the evident option, which is not considered in this study, is an individual biomass boiler for every building. For reasons of air quality and local availability of biomass, this solution must however be considered as the exception rather than the rule. The second option would be a heat pump, but given the high energy demand of the building this will come with technical challenges and/or high electricity uses[21]. Biogas (supplied through the original natural gas network) will only occur in (very) limited cases for the reasons of limited biomass availability mentioned higher. For the majority of the buildings, low carbon stand alone will only work well through deep retrofit and a switch to all-electric functioning with heat pumps. The deep retrofit measures help moreover to limit the increase of the electricity demand by the heat pumps, and hence the need for grid reinforcements.
- High temperature district heating: this is the most profitable scenario, as far as a carbon-free HT DH source is available. Such source may be based on biogas or biomass (on a large scale deployed with fume cleansing), solar heat, industrial waste heat or deep geothermal heat. These sources are only available at certain locations and/or in limited quantities, compared to the average societal heat demand – see also further. Moreover, and as the concerned buildings will typically not be deeply retrofitted to minimize the TCO, the heat demand remains high. This scenario is interesting but will in practice often have to be reserved for areas with no other feasible solution, e.g. heritage areas.
- Low temperature district heating: buildings connecting to the network need to rely on a booster heat pump for upgrading the temperature level of the incoming heat. The operational cost of this scenario becomes very important, even to such level that the TCO of the solution is higher than for any scenario with deep retrofit – deep retrofit combined with a heat pump as much as deep retrofit with a connection to a DH network. Moreover, as electricity use for this scenario is substantial and adds up to the existing consumption of household appliances, the current electricity grid may require substantial reinforcing as well. The grid operator will recover these reinforcement costs from the end user. It will result in the individual building owner paying twice: once for the high electricity consumption and once more for upgrading the grid infrastructure.

21 Another possible option, using solar boilers and hot water buffers for space heating, cannot compete with scenarios combining PV and a heat pump, in terms of TCO.

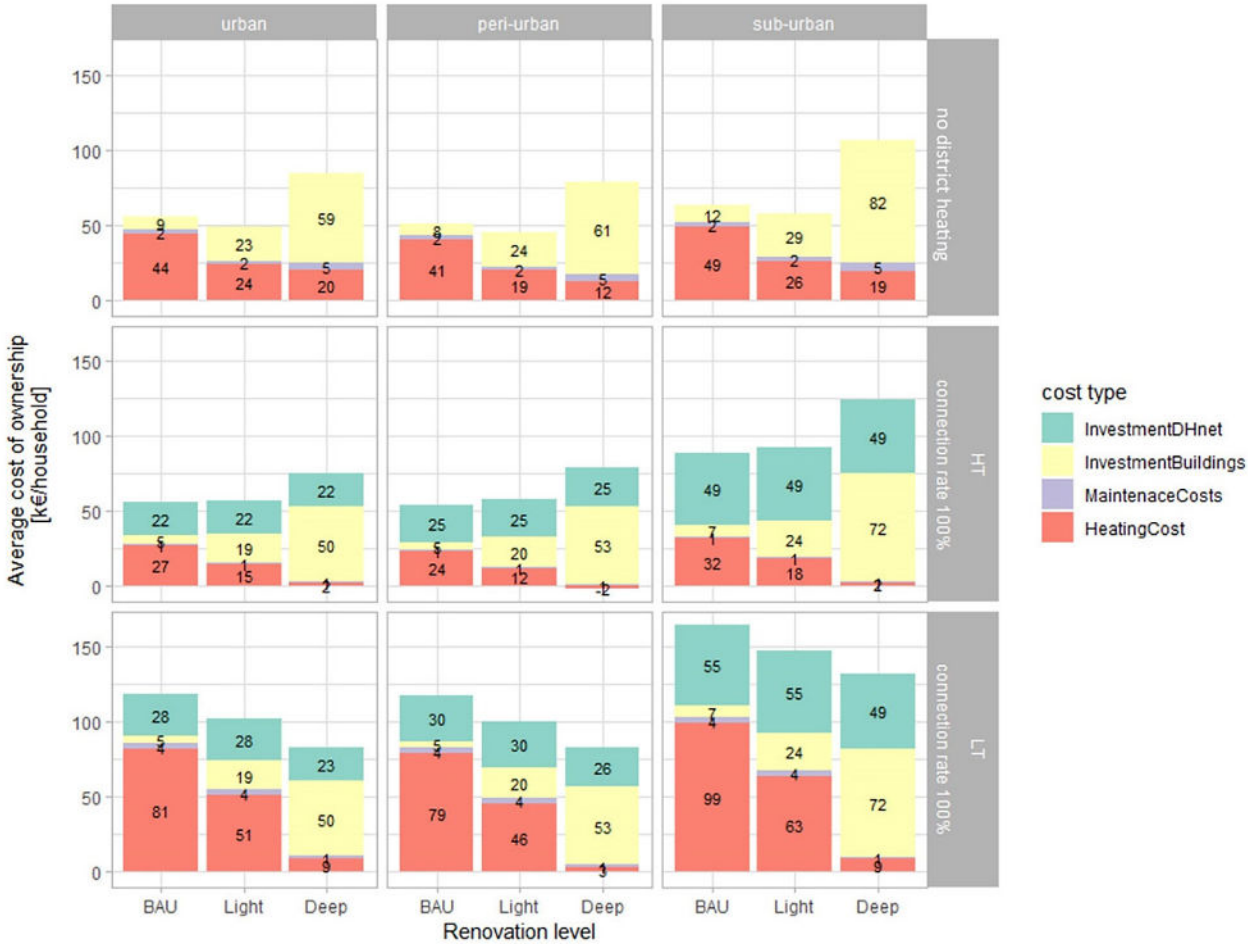


Figure 18: Breakdown of total cost of ownership among cost type (30 years horizon, 3% discount rate, 50% attribution of the envelope retrofit cost to the energy related aspects) for a low-cost HT or LT DH source with 100% connection rate to the DH network, compared to no presence of a DH system.

By conclusion, when high carbon emission reductions are required, the only alternative for deep retrofit exists where (low cost) high temperature carbon-free district heating can be rolled out. If the district heating source becomes more expensive, the competitiveness of this solution slightly reduces (Figure 13). The feasible non-DH variant using such source is individual heating with a biomass boiler. This solution should however not be promoted, see higher.

Conclusions from the building perspective

From the perspective of the individual building owner, reverting to light renovation (LR) may often come forward as the most attractive option. This is a fortiori the case with low cost HT DH available. However, if the EU policy goals of 80 to 95% reduction of carbon emissions must be achieved, near 100% renewable energy input becomes mandatory. As a substantial share of the related thermal energy inputs will come at low temperature levels, there are only two major options for buildings:

- Perform deep retrofit and thus have the building fit for low temperature heating through a heat pump or through low temperature district heating (LT DH). The retrofit operations can be performed stepwise, based on a building roadmap, in order to make investments more feasible. In this way these investments can moreover coincide with natural intervention moments such as sale of the building, necessary repairs or general renovation. A building roadmap is hereby strongly advisable in order to avoid sub-optimal interventions (lock-in). It must be noted that deeply retrofitted buildings are also more comfortable and healthy; furthermore they are better prepared for the use of heat pumps and demand response in a dynamic RE provision context;
- Perform light retrofit and revert to the use of a booster heat pump to provide for both domestic hot water (DHW) and space heating at the required high temperature level (HT, 65°C). Although this leads to savings on the building envelope retrofit costs, it leads at the same time to substantial electricity use and thus increased costs over the total life cycle. Total costs will finally outweigh the costs of deep retrofit scenarios.

If light retrofit would be performed as a first step towards later deep retrofit, it should be envisaged in such way that, both from the technical and financial point of view, no lock-in is created.

CO_2 savings of more than 100% are possible because of the installed PV. If indeed there is a net export of PV energy from the building or the district on an annual basis, then this building or district helps to reduce carbon emission outside its own perimeter, resulting in a more than 100% reduction figure for that particular building or district. This should however not be considered as a fully advantageous option: massive deployment of PV will lead to a seasonal balance problem on the electricity grid, where in summer buildings produce a substantial excess of electricity and the reverse occurs in winter with high electricity demand for the heat pumps and limited sunshine available. Current grid capacity may thus become insufficient for handling the transport volumes, both by deployment of heat pumps and PV, imposing expensive grid reinforcements.

Conclusions from the district heating network perspective

Rolling out (low temperature, 4G) district heating is not an evident option when being considered on an investment horizon of 30 years. This adds to the need to consider DHC networks as assets in which society decides to invest based on a longer time horizon (typically starting from 40 years) and with particular goals in mind – the low carbon society and 100% renewable energy input in particular.

The influence of the connection rate to the DH network is dependent of the type of network: HT versus LT. This is mainly due to the chosen set up of the scenarios, whereby badly insulated buildings need booster heat pumps to connect to LT DH systems.

Resultantly, for HT DH cases, the TCO only slightly increases with decreasing connection rates. The business cases are thus not fundamentally altering between a 50% and 100% connection rate. It means that once the DH network has been rolled out, the advantage of connecting more homes exists but is limited, at least from the point of view of the TCO for society and not in terms of the business case for the DH network operator. In urban areas, stand-alone, all-electric deep retrofit always remains more expensive except where buildings are systematically deeply retrofitted and at the same time only for 50% connected to the DH system: this scenario is clearly a waste of means by sub-optimally introducing a 'double' solution.

For LT DH cases, the TCO increases with increasing connection rates, especially where expensive booster heat pumps are needed for the BAU or lightly retrofitted buildings. The contra-intuitive conclusion that more connections bring on a worse business case, is fully due to the situation that staying with a stand-alone, fossil fuelled home is cheaper than connecting it to a DH system for which it is not prepared. Together with the high electricity price, this leads to a financial punishment for connecting to the DH network. It remains however a solution that may make sense for lowering the overall carbon emissions.

For all scenarios it must be kept in mind that the availability of high temperature district heating (HT DH) will be the exception rather than the rule, for the following reasons:

- Availability of waste incineration as a cheap HT source will reduce over time as the circular economy takes shape. Waste heat shall in this perspective often be considered as a transition source. It will kickstart the roll-out of DH systems, after which upgrading to other 4G sources will be made easier. A similar reflection could be made for a particular case in Flanders, the city of Antwerp, where a huge industrial waste heat potential is available from the petrochemical industry (an estimated 1000 MW at 80 to 120°C or more[22]). We see an exceptionally good case for HT DH roll-out, but with possible switches away from traditional fossil fuel-based production towards bio-based products, the future availability of this source may come under threat.
- Compared to the societal heat demand, biomass is only available in limited quantities especially if one adopts sustainability criteria implying that waste streams are the norm for energetic use of biomass and that virgin biomass shall in a principle not be used for energy production;
- In a similar vein deep geothermal energy can only be applied at given geographical locations and comes with higher costs and challenges as source depth increases;
- Solar boilers provide an attractive source but are expensive and equally limited in capacity (or need large deployment surfaces in order to provide heat in sufficient quantities);

Two other cases studied at EnergyVille illustrate this context:

- In a recently delivered climate action plan for the city of Roeselare, which has one of Flanders' most extensive urban DH systems in place, the available maximum heat potential that could be delivered from the waste incineration plant feeding the network would amount to some 130 GWh per year. For comparison, the present heat demand from the built environment in Roeselare amounts to about 680 GWh per year (depending on the severity of winters)[23].

22 Gemeentelijk Havenbedrijf Antwerpen (2012), Havenwarmte – Haalbaarheidsonderzoek naar de valorisatie van industriële restwarmte in de haven van Antwerpen, MIP2 Heat study. The study identifies some 480 MW waste heat available at 80°C-120°C and estimates that this figure may be doubled when excess heat sources of more than 120°C are taken into account as well.

23 Klimlaat+plan Roeselare (Roeselare Climate Action Plan): this document can be downloaded from https://www.klimaatswitch.be/klimaatplan

- In the framework of the EU FP7 project City-zen and under the coordination of TU Delft, development scenarios for urban retrofit in Amsterdam have been analysed[24]. At present, the city already imports waste per ship (e.g. from the United Kingdom) in order to feed its waste incinerator and the connected DH network. When assessing potentials into more detail, it soon became obvious that HT heat sources must be strictly reserved for those applications where they are the only viable solution. One such context was the historic city centre, listed as UNESCO patrimony, and where hardly any retrofit interventions are allowed. Wherever possible, turning to LT heat sources must be pursued. If LT heat is available at low cost, this still implies retrofit for those buildings that do not have a good thermal performance. In practice this means that the LT source must be combined with a certain degree of retrofit.

Another important boundary condition relates to the seasonal heat balance. Heat sources like waste heat and solar heat lead to a seasonal balancing challenge: the heat production is continuous over the year or peaks in the summer whereas the demand peaks in the winter, causing the need to buffer heat over long periods. When buildings are not being renovated, the buffered heat shall moreover be available at high temperature which increases the challenges and related costs. At present the costs of buffering e.g. solar heat have been included in the heat cost (storage at an investment cost of 25 €/m³ in water-based heat buffers is feasible) but two other parameters nevertheless remain critical: the surface of solar collector fields needed, and the size of the related buffers. These have important spatial impacts and the available land or space may not be sufficient to fill in the demand when no reduction measures for the energy demand are being taken. Other factors like aesthetic objections are also expected to interfere.

Conclusions from the societal energy demand perspective

The current heat demand of the building stock is so high that in many cases sustainably supplying all required (carbon-free) heat for a non-retrofitted building stock will appear to be impossible, even if this supply is stretched to its technical limits (and thus making abstraction of limiting factors like the current spatial planning regulations regarding RE production).

Moreover, heat sources like waste heat and solar heat lead to a seasonal balancing problem: the heat production is continuous over the year or peaks in the summer whereas the demand peaks in the winter. When buildings are not being renovated, the buffered heat shall moreover have to be available at high temperature which increases the challenges and related costs.

All of these factors will push back to at least a partial retrofit of the building stock, be it for technical, spatial or financial reasons. Given the dependency on context, and more in particular the availability of sufficient low carbon DH resources, only a case by case trade-off will reveal the real possibilities in situ.

In general, we can conclude that the real challenge does not reside at the level of the individual district, but at the urban or regional scale. It is at the higher scale level that the supply and demand of available (heat) resources command the viable options. Within those boundary conditions, sources and interventions must be allocated depending on every single context at the district levels.

A similar challenge appears for electricity: as on the one hand more PV is installed and on the other hand more heat pumps come into operation, the risk of daily or seasonal imbalance on the grid sharply increases. Again, this is a problem that must be solved at the higher scale levels and by bringing in additional features such as local electricity and heat storage.

Once the regional energy balances have thus been considered, decisions can be made to choose the lowest TCO solutions at the level of the individual urban districts. Depending on the location with its renewable energy potential, the urban density and the state of the building stock, switching to stand-alone and all-electric deep retrofit or to varying degrees of retrofit combined with district heating provision will come forward as the best option from a combined technical and financial point of view.

General conclusions

The above observations lead to the conclusion that, independent of the presence of DHC networks, it is in the long term recommended to perform a deep retrofit on all buildings except for those cases where, for particular reasons like heritage conservation or the close and ample availability of high temperature heat, reverting to a high temperature DHC network is the preferred option.

The incentive for deep retrofit of the building stock is however not only a matter of energy, but also of health, comfort, real estate value and future-proofedness.

The influence of the assignment rate of building envelope retrofit costs on the preferred choices is considerable. The adopted perspective on building investments (and hence, the adopted building roadmaps) is steered by multiple and strongly connected values. Whether we consider an intervention as just an 'energy burden' or as an investment in the building as a whole value asset, makes a substantial difference.

24 City-zen roadmap show Amsterdam: essential materials can be downloaded from http://www.cityzen-smartcity.eu/energy-transition-road-map-amsterdam-dutch/

District heating networks must be considered as a solution that helps to realise the EU climate goals from a long term investment perspective. A careful local analysis must clarify where they will be preferably rolled out. Well-prepared heat zoning plans will therefore greatly support such strategy.