HeriTACE

R^2ES-Based Energy Supply Concepts for Heritage Buildings in Historical Neighbourhoods

Deliverable D4.1

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Executive Summary

Renovating and rehabilitating historic buildings require a careful approach to balance cultural preservation with modern needs such as energy efficiency, structural integrity, and occupant comfort. In addition to energy efficiency, there is a growing demand to increase the use of renewable and residual energy sources for buildings and to reduce reliance on fossil fuels. This process involves tailored assessments to ensure interventions prioritise conservation and avoid altering the building's defining heritage values.

This report identifies and categorises renewable and residual energy production and supply systems and components, focusing on their suitability and impacts for heritage building interventions. The report is based on a review of existing systems in the literature and on the market, as well as some innovative systems.

The report also introduces various neighbourhood-level energy production and supply systems. Neighbourhood-level systems are still relatively uncommon, and there is untapped potential for increasing the share of renewable and residual energy sources for blocks of buildings.

Pre-renovation baselines, as well as typical renovation baselines, are described for building archetypes and case study neighbourhoods, as defined in Deliverable 5.1 and data collected from case study buildings by local partners. Energy production and supply baselines are created to understand the current energy supply concepts for heritage buildings and to establish references for later stages in the project to compare the impacts of improvements.

Longlists of different energy supply systems are created and described in this report. Opportunities and constraints are analysed for different energy supply systems for buildings and neighbourhoods. Finally, the study proposes shortlists of tailored energy production and supply concepts for the various building archetypes and neighbourhoods in different case study countries studied in the HeriTACE project. The proposals consider the specific requirements of different climate zones (introduced in Deliverable 3.1) and boundary conditions from archetypes and case study neighbourhoods.

For each building archetype, multiple scenarios are explored, presenting a range of energy production and supply concepts including new installations and hybrid systems. These scenarios are created to accommodate unique building constraints, such as heritage preservation, space limitations, and existing infrastructure at the neighbourhood level, while considering energy production and supply system performance.

This deliverable should be considered in combination with building envelope (Deliverable 2.2) and HVAC concepts (Deliverable 3.1) to achieve a holistic overview of the retrofit solutions and scenarios for the heritage building archetypes targeted in HeriTACE. The concepts will be applied to the building and neighbourhood energy modelling to assess their performance (Tasks 3.2, 3.5, and 4.5).

Abbreviations and acronyms

Acronym	Description
1GDH, 2GDH, 3GDH, 4GDH, 5GDH	1st, 2nd 3rd or 4th Generation District Heating
AC	Alternating Current
ASHP	Air Source Heat Pump
BIPV	Building-Integrated Photovoltaics
CHP	Combined Heat and Power (Typically referred to district heating plant)
DC	Direct Current
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
ERV	Energy Recovery Ventilation
GSHP	Ground Source Heat Pump
HHV/GCV	Higher Heating Value (HHV) / Gross Calorific Value (GCV)
HP	Heat Pump
HRV	Heat Recovery Ventilation
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
KPI	Key Performance Indicator
LHV/NCV	Lower Heating Value (LHV) / Net Calorific Value (NCV)
PV	Photovoltaics (Typically referred to technology converting solar energy to electricity via Photovoltaics panels)
R2ES, R²ES	Renewable and Residual Energy Sources
PVT	Solar panel that combines photovoltaic panel and solar thermal collector
STC	Solar Thermal collector
V2G	Vehicle-to-Grid. Refers to the technology that allows electric vehicles (EVs) to not only draw power from the grid to charge their batteries, but also to send power back to the grid.
WLFCU	Water Loop Fan Coil Units

Terminology

Term	**Description**
System/technology	a single, stand-alone heat or cold generating/storage technology, for example a type of heat pump or solar thermal collectors
Concept/scenario	the combination of multiple systems to create a complete idea on how to provide heating/cooling/DHW
Longlist	a list containing all possible, though relevant, systems before any selection and application of (climate) boundary conditions. One general list.
Intermediate list	subset of the longlist after selection and application of all boundary conditions, including climate, thus containing only the feasible systems that will be used to build the concepts. One list for each climate zone.
Shortlist	a list containing all interesting concepts. Combinations of the systems in the intermediate list. One for each climate zone.

1. Introduction

By 2050, the European Union (EU) aims to reach climate neutrality. The European Green Deal and the New European Bauhaus are key initiatives designed to create a sustainable and inclusive society through cross-sector collaboration and innovative approaches.

Research has consistently emphasised the importance of sustainably using and transforming the existing built environment (Fufa et al., 2021). A significant challenge in this transition is the requirement to renovate our housing stock, which accounts for 26.2% of the EU's final energy consumption (Eurostat, 2025). Historic cities in Europe present additional complexity. It is clear that historically valuable buildings must be preserved to respect their heritage and societal values. However, it is unclear how to balance the conservation of individual buildings with the overarching goal of achieving climate neutrality for the entire building stock. In addition to the fact that changes to heritage buildings require customisation, there is also a need for a framework to assess these different aspects at the building or neighbourhood level and to provide insights and solutions to meet this challenge.

Improving buildings' energy efficiency alone will probably not be enough to achieve climate neutrality. We must also phase out fossil fuels and increase the use of renewable and residual energy sources for buildings. This will require implementing renewable and residual energy production and supply systems in buildings and utilising the potential of the local neighbourhood.

The HeriTACE project investigates how to future-proof our heritage buildings in a manner that bridges the gap between heritage restrictions and environmental ambitions. The project focuses specifically on small to medium-sized heritage townhouses constructed before 1945. Achieving the ambitious goal of climate neutrality requires a multidisciplinary team to consider all aspects of renovation: heritage value, energy use, user comfort, functionality, cost-effectiveness, and waste management. Heritage restrictions often preclude generic solutions, necessitating innovative approaches to building envelope, heating, ventilation, and heat/cold generation.

The objective of this report is to provide long and shortlists for energy production and supply systems for heritage buildings and neighbourhoods and to serve as a logbook for constraints and opportunities.

This report focuses on energy production and supply systems and their implementation in heritage buildings to increase the use of renewable and residual energy. First, this report introduces pre-renovation and renovation scenarios, typical existing scenarios for energy production and supply systems for different heritage building archetypes and neighbourhoods.

After the baselines, potential renewable and residual energy systems that might be suitable for heritage buildings and neighbourhoods are introduced. This will form the basis for a longlist of different energy production and supply systems.

Analysis of the suitability of different energy supply systems for buildings and neighbourhoods requires identifying constraints and opportunities. This analysis considers several aspects such as heritage, city centre layout, different climate zones (introduced in

Deliverable 3.1), and where and how systems can be integrated. The analysis is conducted using a multidisciplinary approach involving technical experts as well as heritage experts.

Finally, the report introduces proposed shortlists of energy production and supply concepts for heritage buildings and neighbourhoods. These concepts will be applied to building and neighbourhood energy modelling to assess their performance in later stages of the HeriTACE project (Tasks 3.2, 3.5, and 4.5).

2. Energy Supply Baseline Scenarios

The baseline scenarios in this chapter describe energy supply systems for two different baselines: a Pre-renovation baseline and a Renovation baseline.

A pre-renovation baseline, the reference situation of the building as in the present state is chosen, assuming no recent renovation has taken place to implement a range of recent EPBD-inspired renovation measures. This corresponds to the situation of the building after some 'old renovation' measures, as would have been done during a renovation in the period 1990-2010.

The renovation baseline corresponds to a renovation according to common practice today. In practice we mostly observe stepwise (or element-wise) renovations of the building, where the various elements are renovated with common practice renovation solutions, and fulfil the local temporary energy-related requirements, such as requirements related to the local EPBD implementations.

Generalised baselines were created based on interdisciplinary data collection from actual case study buildings. Detailed data from case study buildings is available in HeriTACE SharePoint and can be accessed by parties involved in the project. Data from energy supply systems were analysed and, based on the information and analysis, general baselines are proposed for different archetypes. The analysis also takes into consideration the upcoming EPBD regulations and information from each country on how fossil fuels as a heat source for buildings are regulated. There are national regulations for phasing out oil and gas, varying from country to country. Figure 1 illustrates national regulations for the use of oil and gas for existing buildings and new buildings. No oil or gas are proposed for the renovation baseline where it is known to be phased out in the near future or already phased out today.

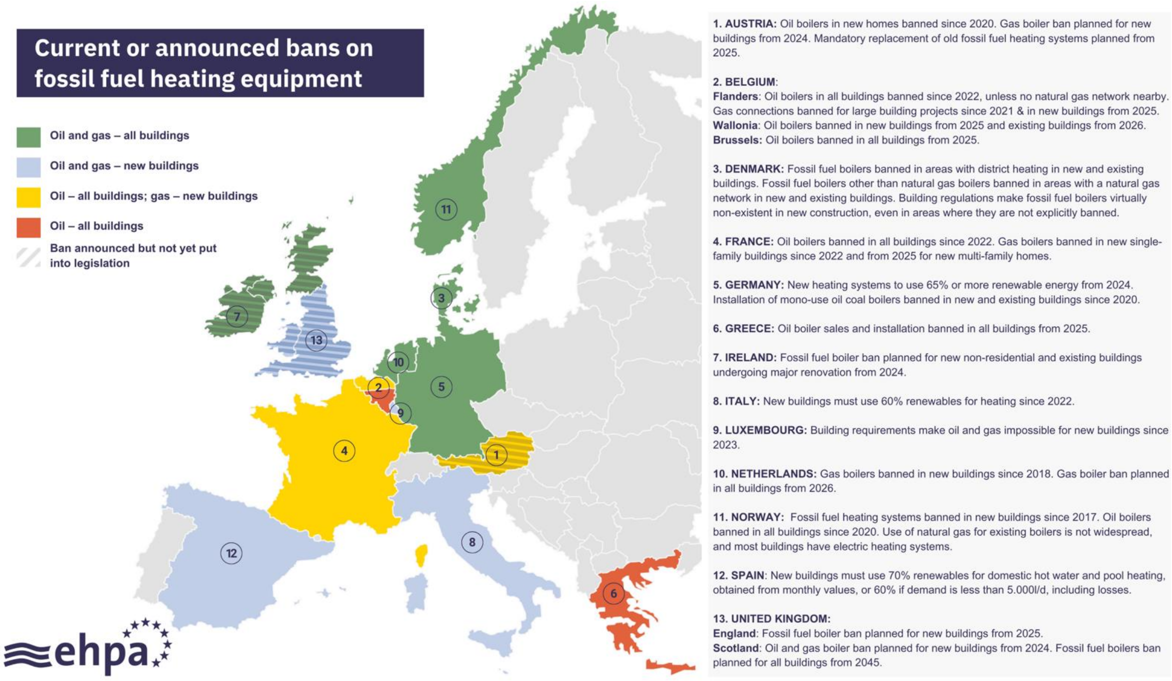

Figure 1: Current or announced bans on fossil fuel heating equipment (The European Heat Pump Association AISBL, 2024).

2.1. Belgium

For Belgium, data were available from 14 different case study buildings. The energy supply systems for these buildings are as follows:

Heating

- All 14 case study buildings are equipped with a condensing gas boiler. One of the buildings is also equipped with an oil boiler and wood heating in addition to the condensing gas boiler.

The total installed power varies from 24.6 kW to 66.0 kW for buildings equipped with condensing gas boilers. The installed power for the building that has oil and wood in addition to the condensing gas boiler is 124.7 kW. Supply water temperatures from the heat source to emission systems vary from 55 °C to 72 °C.

Cooling

Two of the case study buildings are equipped with an air-conditioning (air-con) cooling unit. The other buildings have no active cooling systems.

Domestic Hot Water

- 7/14 case study buildings are equipped with a condensing gas boiler.
- 2/14 case study buildings are equipped with a traditional non-condensing gas boiler.
- 1/14 case study buildings are equipped with a condensing gas boiler + oil boiler.
- 2/14 case study buildings are equipped with electric boilers.
- 2/14 case study buildings are equipped with a solar boiler assisted by a gas boiler.

In addition to gas boilers, there are separate electric boilers for DHW heating in several case study buildings. For case study buildings with a gas boiler, the total installed power varied from 20.7 kW to 82.6 kW. For case study buildings with an electric boiler, the total installed powers are 2.7 kW and 3.4 kW.

Solar System

- 5/14 case study buildings are equipped with PV panels.
- 2/14 case study buildings are equipped with a solar boiler assisted by a gas boiler.

Storage

- In addition to gas and electricity boilers, one of the case study buildings has a 15 kWh electric battery connected to a PV panel.

Total annual gas energy use varies from 7.5 MWh/year to 29.5 MWh/year. Heated area data are available from 7 buildings. Specific gas energy use varies from 22.6 kWh/heated m² to 96.0 kWh/heated m². Reported energy use data is not normalised.

In a recent research publication (Maton et al., 2024), energy calculation methods and real consumption are compared for different Belgian Heritage Townhouses. This study provides valuable information about the difference between different calculation methods and real consumption. In Figure 2, the results of this study, as well as real consumption for 7 case study buildings per heated net area, are represented.

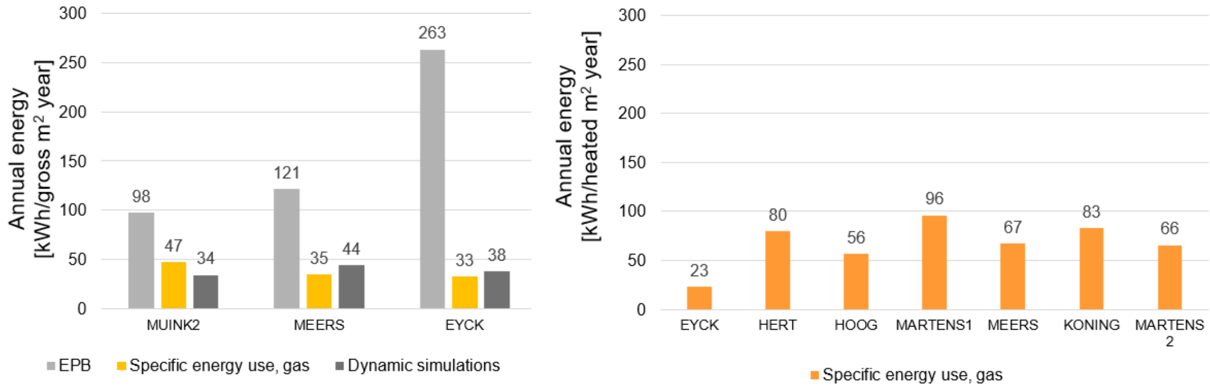

Figure 2: Energy calculation method comparison (left) and Case study buildings real annual energy use (right).

Data from the right-side chart cannot be directly compared to data from the left-side chart because units are different. The left-side chart is reported by gross m², whereas the right-side chart is reported by heated m².

The right-side chart provides an interesting insight into the difference between calculated, simulated, and specific energy use. The left-side chart, then, provides some indication of how much real energy use can vary from building to building when considering annual energy use per heated m².

Neighbourhoods

Two neighbourhoods have been selected from the city of Ghent. Both neighbourhoods provide different options for utilising renewable and residual energy sources and energy storage.

Sint-Michielsplein is a neighbourhood where the central building is St Michiels Church. The streets are narrow, and the buildings along the streets are attached to each other. Most of the buildings are dwellings from various construction periods and typologies. There is an office building, and beneath this, there is a large underground parking facility owned by the city of Ghent. The River Leie passes through the neighbourhood.

Vlaanderenstraat is a neighbourhood with tightly packed buildings along the sides of the streets. A diversity of functions is available in this neighbourhood, including residential and commercial. This provides opportunities for exchanging and sharing energy between different functions. To the south and east of the neighbourhood, there is the River Muinkschelde, which could be a potential source of renewable energy. To the north, close to the neighbourhood, there is an underground parking facility. The district heating network is located in the southern part of the neighbourhood. However, at present, the company Luminus has no plans to expand the network and connect it to individual dwellings.

In the city of Ghent, there is a district heating network supplied by the Luminus gas power plant. Currently, several large buildings are connected to this network, such as the hospital, university, and a swimming pool. However, residential buildings around the case study neighbourhoods are not connected to heating network. Currently, the company Luminus has no plans to expand the network to connect individual dwellings to the district heating network.

2.1.1. A Pre-Renovation Energy Supply Baseline Scenario

Based on case study buildings and expertise of local partners, a pre-renovation baseline for Belgium building archetypes is proposed (see Figure 3):

Heating

- Energy scenario 1, pre-renovation: Centralised gas boiler, located in the cellar
- Energy scenario 2, pre-renovation: Apartment based gas boiler

Condensing gas boilers started to emerge in the late 1990s, especially for new buildings and major renovations. From the mid-2000s to 2010, condensing boilers became the standard choice for new buildings and major renovations. The average lifespan of a gas boiler is 10-20 years.

During the pre-renovation period (1990-2010), both non-condensing and condensing gas boilers were available. However, due to their limited lifespan, most of the non-condensing gas boilers from this era are probably already replaced.

Cooling

- No active cooling systems. Opening windows are used for cooling.

Domestic Hot Water

- Energy scenario 1, pre-renovation: Decentralised electric boilers (with integrated storage).
- Energy scenario 2, pre-renovation: Apartment-based gas boiler that provides space heating also supplies DHW to the bathroom. Other DHW is supplied by decentralised electric boilers (with integrated storage).

Solar System

- No solar systems.

Storage

- No additional energy storages.

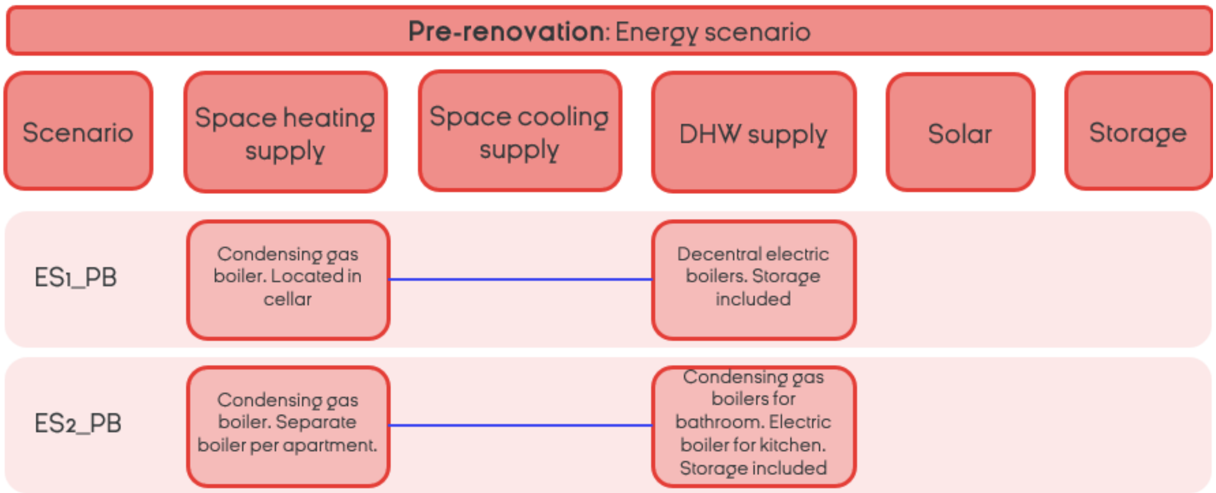

Figure 3. Proposed pre-renovation energy scenarios for Belgium.

ES1_PB: Gas boiler, electric DHW boilers

The first energy scenario is applicable to the middle-class townhouse, the modest house, and the private mansion. In this configuration, space heating is provided by an old condensing gas boiler with low efficiency, that is located in the cellar. Domestic hot water (DHW) is generated locally at the tap points through separate electric boilers installed in the bathrooms and kitchen, each equipped with integrated storage to ensure adequate hot water supply. No cooling system is included in this scenario, nor is there any provision for energy storage or the integration of solar energy systems.

ES2_PB: Gas boiler per app., electric DHW boilers

The second energy scenario is exclusively applicable to the multi-family townhouse archetype and differs from the previous scenario primarily due to the presence of multiple residential units within a single building. In this configuration, each apartment is equipped with its own condensing gas boiler with low efficiency, providing space heating. DHW for the bathroom is also produced by the same gas boiler within each unit. However, in the kitchen, DHW is supplied by a dedicated electric boiler with integrated storage. As with the first scenario, no mechanical cooling system, energy storage, or solar energy technologies are included.

2.1.2. A Renovation Energy Supply Baseline Scenario

Based on case study buildings and expertise of local partners, a renovation baseline for Belgium building archetypes is proposed:

Heating

- Energy scenario 1, pre-renovation: Centralised new gas boiler, located in the cellar
- Energy scenario 2, pre-renovation: Apartment based new gas boiler

Cooling

- No active cooling systems. Opening windows are used for cooling.

Domestic Hot Water

- Energy scenario 1, pre-renovation: Decentralised new electric boilers (with integrated storage).
- Energy scenario 2, pre-renovation: Apartment-based new gas boiler that provides space heating also supplies DHW to the bathroom. Other DHW is supplied by new decentralised electric boilers (with integrated storage).

Solar System

- Energy scenario 1 and 2: Small amount of PV panels. Roof installation, positioned on the most solar-exposed roof surface.

Storage

- No additional energy storage.

Figure 4 represents proposed renovation baselines for Belgium building archetypes.

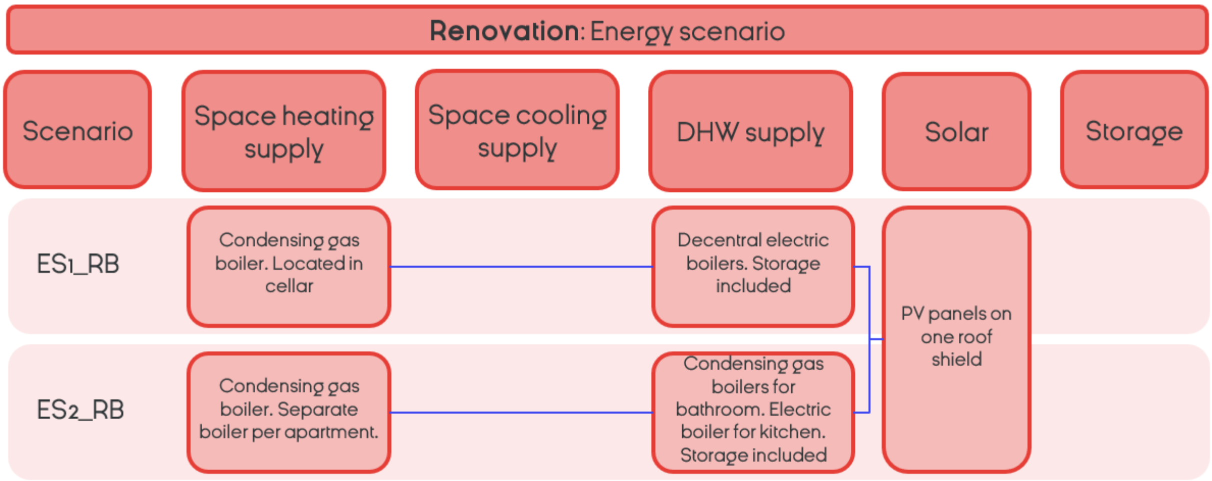

Figure 4. Proposed renovation energy scenarios for Belgium.

ES1_PB: Gas boiler, electric DHW boilers

The first energy scenario applies to archetypes that may retain single-family (or office) use after renovation – specifically, the middle-class townhouse, the modest house, and the private mansion. The renovation baseline heating supply system remains largely consistent with the pre-renovation baseline, with the notable upgrade to a high-efficiency contemporary condensing gas boiler for space heating. DHW continues to be provided locally via decentralized electric boilers installed near the tap points. In addition, a limited installation of photovoltaic (PV) panels is assumed, positioned on the most solar-exposed roof surface.

ES2_PPB: Gas boiler per apartment, electric DHW boilers

The second energy scenario is relevant for archetypes that accommodate multi-family use after renovation, such as the middle-class townhouse, private mansion, and multi-family townhouse. In this case, each apartment is equipped with an individual condensing gas boiler for space heating, also supplying DHW to the bathroom. Kitchen DHW is provided by a separate electric boiler with integrated storage. As in the first scenario, a limited number of PV panels is assumed on the most favourable roof area for solar exposure.

2.2. Norway

For Norway, data were available from three different case study buildings. The energy supply systems for these buildings are as follows:

Heating

- All three buildings are heated using electricity as main energy source. Electric heaters are distributed in different rooms.
- One of the buildings has fireplace in kitchen equipped with iron stove.
- One building is equipped with air-to-air heat pump.
- One building is equipped with electric underfloor heating in bathroom.
- One building has multiple heating system; electrical hydronic underfloor heating, electric heaters and wood stove. Heating is operated by owner so that underfloor heating and electric heaters has fixed set points and wooden stove is used if there is additional need for heating.

For one building there are data available for individual electric heaters. The installed power for individual electric heater varies between 400 W to 1300 W.

Cooling

- No active cooling systems. One building has air-to-air heat pump, but it is used for heating.

Domestic Hot Water

- All three case study buildings are equipped with electric boilers.

Solar System

- No solar systems.

Storage

- In addition to electric boilers, there are no additional energy storage systems.

For one building the total electricity consumption, including heating and other electricity was 20 MWh/year. Another building there is data available for electricity consumption from October 2024 to March 2025 Total electricity use in this case, including heating and other electricity use was 6.7 MWh.

Neighbourhood

In Norway, the neighbourhood Bakklandet from the city of Trondheim has been selected as a case study neighbourhood. West side of the Bakklandet the river Nivelda is flowing. Streets are narrow, and buildings are tightly packed in the neighbourhood.

District heating covers about 30% of Trondheim's heating needs. District heating is primarily produced using residual waste. The main facility for this is the incineration plant at Heimdal, which burns waste collected from central Norway to heat water (Statkraft, n.d.).

Additionally, the sewage processing plant is connected to the district heating network. This is because a by-product of sewage treatment is methane gas, which gets collected and burned to heat water that circulates in the district heating network (Nikel, 2022).

2.2.1. A Pre-Renovation Energy Supply Baseline Scenario

Based on case study buildings and interviews with local partners, a pre-renovation baseline for Norway building archetypes is proposed:

Heating

- Energy scenario 1, pre-renovation:
  - Electric heaters distributed in different rooms.
  - Wood burning stoves.
  - Electric underfloor heating in bathrooms.
- Energy scenario 2, pre-renovation
  - Wood burning stoves
  - Direct electric heating elements

Wooden fireplace or stoves in apartments are used for heating during winter when the electricity price is high.

Cooling

- No active cooling systems. Opening windows are used for cooling.

Domestic Hot Water

- Electric boiler including tank.

Solar System

- No solar systems.

Storage

- No additional energy storage.

Figure 5 represents proposed a pre-renovation baseline for Norway building archetype.

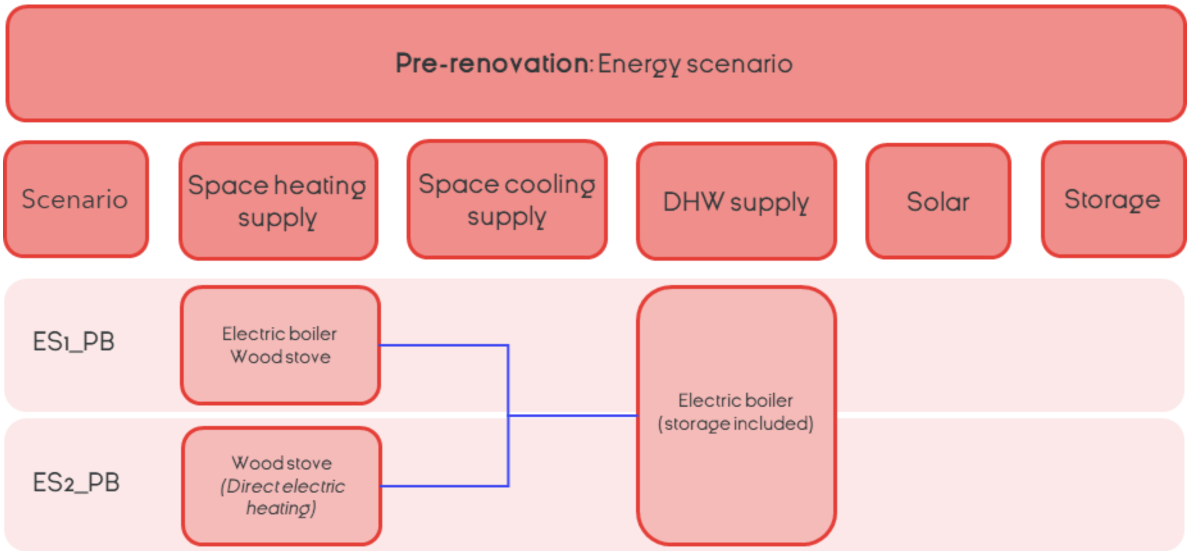

Figure 5. Proposed pre-renovation energy scenario for Norway.

ES1_PB: Electric boiler, wood-burning stove

For the first pre-renovation energy scenario, space heating is provided by an electric boiler. This electric boiler provides the necessary hot water for the central hydronic heating system. Wood-burning stoves are typically present in living rooms, to provide additional heating in winter. Domestic hot water is heated using electric boilers that include storage tanks. No solar systems or additional energy storages are present.

ES2_PB: Electric direct heating, wood-burning stove

For the second pre-renovation energy scenario each room has an individual electric heater (or electric underfloor heating). Apartments also have wood-burning stoves that are used for heating during winter when electricity prices are high. Domestic hot water is heated using electric boilers that include tanks. No solar systems or additional energy storages are present.

2.2.2. A Renovation Energy Supply Baseline Scenario

Based on case study buildings and interviews with local partners, a pre-renovation baseline for Norway building archetypes is proposed:

Heating

- Energy scenario 1, renovation:
    - Electric heaters distributed in different rooms
    - Wood burning stoves.
    - Electric underfloor heating in bathrooms.
- Energy scenario 2, pre-renovation
    - Wood burning stoves
    - Direct electric heating elements

Wooden fireplace or stoves in apartments are used for heating during winter when electricity price is high. If bathrooms are renovated, additional insulation can be considered installed at the floor. This would increase the efficiency of the electric underfloor system.

Cooling

- No active cooling systems. Opening windows are used for cooling.

Domestic Hot Water

- Electric boiler including tank.

Solar System

- No solar systems.

Storage

- No additional energy storage.

Figure 6 represents proposed a renovation baseline for Norway building archetype.

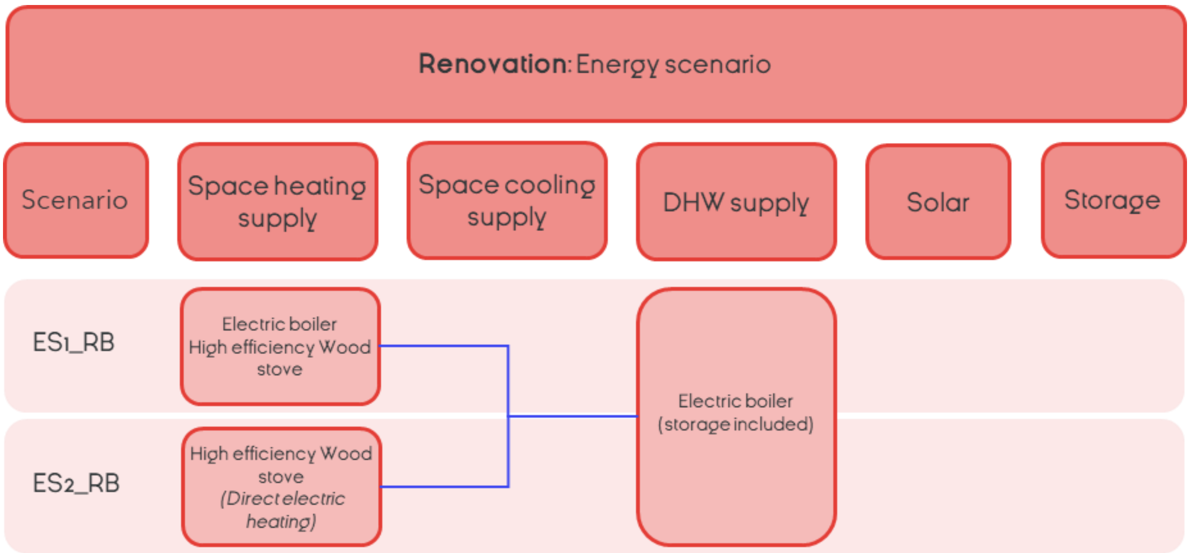

Figure 6. Proposed renovation energy scenario for Norway.

The renovation baseline energy scenarios are similar to the pre-renovation baselines.

ES1_RB: Electric boiler, wood-burning stove

Space heating is again provided by an electric boiler, that produces the necessary hot water for the central hydronic heating system. Wood-burning stoves are still assumed in living rooms, but Older coal-burning or inefficient wood stoves and open fireplaces are replaced by modern, high-efficiency models. Domestic hot water is heated using electric boilers that include storage tanks. No solar systems or additional energy storages are present in the renovation baseline.

ES2_RB: Electric direct heating, high efficiency wood-burning stove

Direct electric heating is providing the space heating (through electric heaters and underfloor systems). Wood-burning stoves are still assumed in living rooms, but Older coal-burning or inefficient wood stoves and open fireplaces are replaced by modern, high-efficiency models Domestic hot water is heated using electric boilers that include tanks. No solar systems or additional energy storages are present.

2.3. Estonia

For Estonia, data are available from five different case study buildings. Two of the buildings represent the masonry heritage apartment building archetype, and three represent the wooden heritage townhouse archetype. The buildings are multistorey residential buildings. The number of apartments in one building varies from 4 to 34. Typical for Estonian case study buildings is that each apartment has the possibility to choose its own heat source, so in one building, there might be several energy supply systems.

The energy supply systems for these buildings are as follows:

Heating

- 1/5 buildings is connected to district heating. This is the largest of the case study buildings, including 34 apartments.
- 3/5 buildings are equipped mainly with apartment-based gas boilers, where most of the boilers are condensing gas boilers. Some of the apartments also have additional heat sources, typically wood stoves and/or electric heaters.
- 1/5 buildings have a mix of different heating systems. This building has four apartments. Two of the apartments are equipped with air-to-air heat pumps and the other two with wood-burning stoves.

Some of the apartments might also have individual electric heaters. For example, electric underfloor heating is a typical solution for bathrooms in Estonia.

Data for the total installed power are available for some of the apartments that use gas boilers. The installed power varies from 14.0 kW/apartment to 25.0 kW/apartment.

Cooling

- 1/5 buildings are equipped with air-conditioning systems. Two apartments are equipped with air-to-air heat pumps that can be used both for heating and cooling.
- 4/5 buildings have no active cooling systems.

Domestic Hot Water

- 4/5 case study buildings are equipped with gas boilers. Apartment-based gas boilers are the most typical solution.
- 1/5 buildings are equipped with apartment-based electric boilers.

For gas boilers, the installed power for domestic hot water varies from 23.0 kW/apartment to 30.0 kW/apartment.

Solar System

- No solar systems.

Storage

- In addition to gas and electric boilers, there are no additional energy storage systems.

At the time of writing this deliverable, energy consumption data for heating is not available for gas or electricity. For the building where two apartments use wood-burning stoves as a heat source, one apartment estimates using 4 m^3 wood logs during each heating season. The other apartment uses wood briquettes and estimates usage of 800 kg to 1,400 kg wood briquettes per year.

Neighbourhood

In Estonia, the neighbourhood Uus-Maailm, located in the city of Tallinn, has been selected as a case study neighbourhood. Buildings in the area are located in a scattered way, and there are many gardens, streets, and yard spaces around and between the buildings. There are no water bodies in the area.

There is a district heating network available in Uus-Maailm, provided by the company Utilitas Group. Utilitas has established a carbon neutrality plan with the objective to reduce greenhouse gas emissions to zero and increase the share of renewable energy production to 100% by 2030.

Renewable sources, such as biomass, wind, solar, and heat pumps, are fundamental to Utilitas's business strategy for the generation of energy (electricity, heat, and cooling. (OÜ Utilitas, 2024).

2.3.1. A Pre-Renovation Energy Supply Baseline Scenario

Based on case study buildings and interviews with local partners, a pre-renovation baseline for Estonian building archetypes is proposed:

Heating

- Energy scenario 1, pre-renovation: Wood burning stoves.
- Energy scenario 2, pre-renovation: District heating

Cooling

- No active cooling systems. Opening windows are used for cooling.

Domestic Hot Water

- Energy scenario 1, pre-renovation: Apartment-based electric boilers.
- Energy scenario 2, pre-renovation: Apartment based gas heaters.

During the pre-renovation period (1990-2010), non-condensing gas heaters were the mainstream solution.

Solar System

- No solar systems.

Storage

- No additional energy storage.

Figure 7 represents proposed pre-renovation baselines for Norway building archetype.

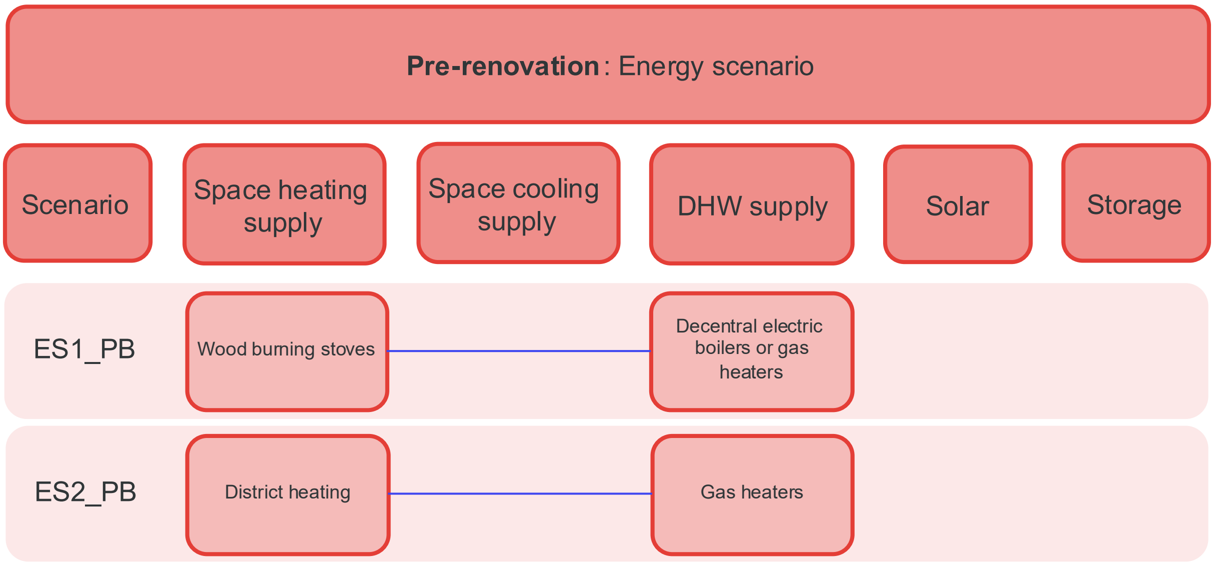

Figure 7. Proposed pre-renovation energy scenario for Estonia.

ES1_PB: Wood burning stoves and electric boilers

This scenario applies to the buildings without connection to district heating network that had initially been built with wood burning stove heating. Domestic hot water is generated using decentral electric boilers.

ES2_PB: District heating and non-condensing gas heaters

This scenario applies to the larger Stalinist style brick apartment buildings with connection to district heating and gas networks – the former is used for space heating and latter for domestic hot water generation.

2.3.2. A Renovation Energy Supply Baseline Scenario

Based on case study buildings and interviews with local partners, a renovation baseline for Estonian building archetypes is proposed:

Heating

- Energy scenario 1, renovation: Mix of apartment-based wood burning stoves and gas boilers.
- Energy scenario 2, renovation: Mix of apartment-based wood burning stoves and air-to-air heat pumps.
- Energy scenario 3, renovation: Apartment-based gas boilers.
- Energy scenario 4, renovation: District heating.

Some of the apartments might also have individual electric heaters, such as electric underfloor heating in bathrooms.

For the renovation scenario, condensing gas boilers are typical when there is a need to renew the gas boiler. However, if gas boilers do not need to be renewed, there might still be some old non-condensing gas boilers in existence today.

Cooling

- No active cooling systems. Opening windows are used for cooling.

Domestic Hot Water

- Energy scenario 1, renovation: Apartment based gas boilers.
- Energy scenario 2, renovation: Apartment based electric boilers.
- Energy scenario 3, renovation: Apartment based gas boilers.
- Energy scenario 4, renovation: Mix of apartment-based gas heaters and electric boilers.

Solar System

- No solar systems.

Storage

- No additional energy storage.

Figure 8 represents proposed renovation baselines for Norway building archetype.

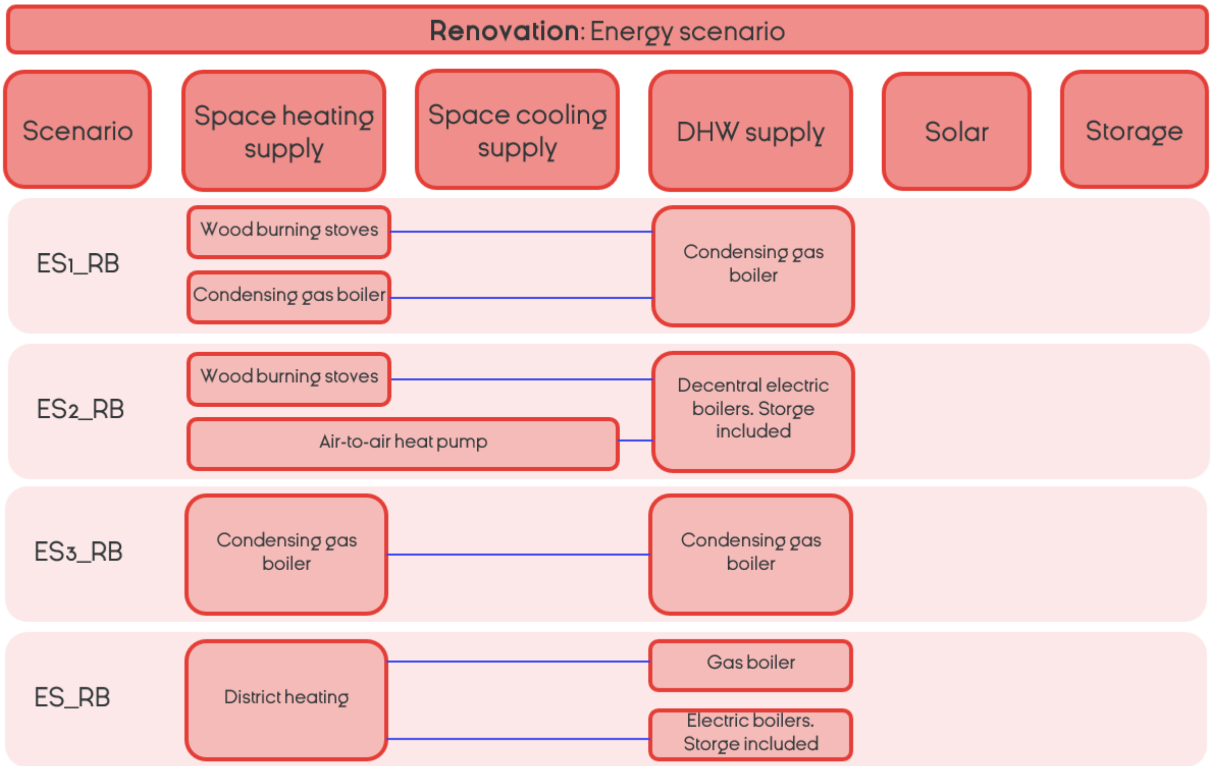

Figure 8. Proposed renovation energy scenario for Estonia.

ES1_RB: mix of wood burning stoves and gas boilers

This scenario applies to smaller buildings with access to gas network. Stepwise retrofit has resulted in partial conversion to apartment-based condensing gas boilers for both space heating and domestic hot water generation. Some apartments fully or partially still use wood burning stoves for space heating.

ES2_RB: mix of wood burning stoves and electric heating

This scenario applies to smaller buildings without access to district heating and gas networks. Stepwise retrofit has resulted in partial adaptation of air-air heat pumps for space heating in some apartments while others still use wood burning stoves. Domestic hot water is generated using decentral electric boilers.

ES3_RB: gas boilers

Here the whole building has converted to apartment-based condensing gas boilers for space heating and domestic hot water generation.

ES4_RB: district heating and mix of gas & electric boilers

This scenario applies to larger buildings with access to district heating and gas networks. The space heating is still supplied by district heating, while the apartment-based gas boilers for domestic hot water generation may have been partly replaced by electric boilers.

2.4. Italy

For Italy, data were available from four different case study buildings. One of the case study buildings is unoccupied. The energy supply systems for these buildings are as follows:

Heating

- All four case study buildings are equipped with gas boilers. One of the buildings, which is currently unoccupied, is equipped with two non-condensing gas boilers, and another building with a condensing gas boiler. For one of the buildings, there is no information on whether the boiler is condensing or non-condensing.

The total installed power for two case study buildings are 139.2 kW and 23.7 kW which includes both for heating spaces and production of domestic hot water. The third case study has an installed power of 255 kW for heating spaces. Supply water temperatures from the heat source to emission are 70 °C for two case study buildings.

Cooling

- 2/4 buildings are equipped with air-conditioning systems.
- 1/4 buildings have no active cooling systems.
- 1/4 buildings no information is available.

One of the case study buildings is equipped with two air-to-air heat pump systems with a total power of 13.6 kW (6.8 kW each). Another case study building is equipped with an air-to-water heat pump system with a total power of 15.5 kW. Both systems can be used for heating as well.

Domestic Hot Water

- 3/4 case study buildings are equipped with gas boilers. One of the buildings has a condensing gas boiler. Two of the buildings have non-condensing gas boilers. For one of the buildings, there is no information on whether the boiler is condensing or non-condensing.
- 1/4 buildings are equipped with electric boilers.

For gas boilers of two case study buildings, the installed power includes both heating spaces and domestic hot water and is reported above under "Heating". Supply water temperatures from the heat source to the domestic hot water supply are 60 °C.

For one case study building, electric boilers are used for heating domestic hot water. This building includes two electric boilers, with a total power of 3.0 kW (1.5 kW each).

Solar System

- No solar systems.

Storage

- In addition to gas and electric boilers, there are no additional energy storage systems.

Total annual gas energy use data is available for two case study buildings. One of the case study building's annual gas energy use was 24.8 MWh/year and 60.0 kWh/heated m². Another case study building's annual gas energy use was 34.0 MWh/year and 97.0 kWh/heated m².

Neighbourhood

In Italy, the city of Mantua has been selected as a case study neighbourhood. Mantua is surrounded by water bodies located to the north, northwest, and northeast of the city. Streets are narrow, and buildings are tightly packed.

There is a well-established district heating network available in the city of Mantua, where about 95% of the high-efficiency cogenerated heat comes from the Enipower Mantua turbogas plant, while the remaining 5% comes from the cogenerator installed at the Carlo Poma Hospital thermoelectric plant in Mantua. The typical composition of the thermal energy produced and distributed by the Mantua district heating system is derived from a mix of:

- High-efficiency cogenerated heat (99%).
- Heat from renewable sources (solar thermal) (0.03%).
- Heat from natural gas backup boilers (0.97%)).

At individual buildings in the Mantua municipal area, thermal energy arrives in the form of superheated water. Thanks to a network of double steel pipes, duly pre-insulated to prevent heat loss and protected by a high-density polyethylene casing, the boiling water transfers the necessary thermal energy to the internal distribution system via a heat exchanger. Thus, solutions based on district heating could be considered cost-effective.

2.4.1. A Pre-Renovation Energy Supply Baseline Scenario

Based on case study buildings and interviews with local partners, a pre-renovation baseline for Italy building archetype is proposed:

Heating

- Energy scenario, pre-renovation: Centralised gas boiler

Condensing gas boilers started to emerge in the late 1990s. Uptake in the adoption of condensing gas boilers took place from the mid-2000s to 2010. By the early 2010s, condensing boilers became the prevalent choice for new installations and replacements.

During the pre-renovation period (1990-2010), non-condensing gas boilers were more typical. Many of the gas boilers installed in the 2000s and earlier will need to be replaced soon if they have not already been replaced.

Cooling

- No active cooling systems. Opening windows are used for cooling.

Domestic Hot Water

- Energy scenario, pre-renovation: Centralised gas boiler (same as heating)

Solar System

- No solar systems.

Storage

- No additional energy storage.

Figure 9 represents proposed pre-renovation baselines for Italy building archetype.

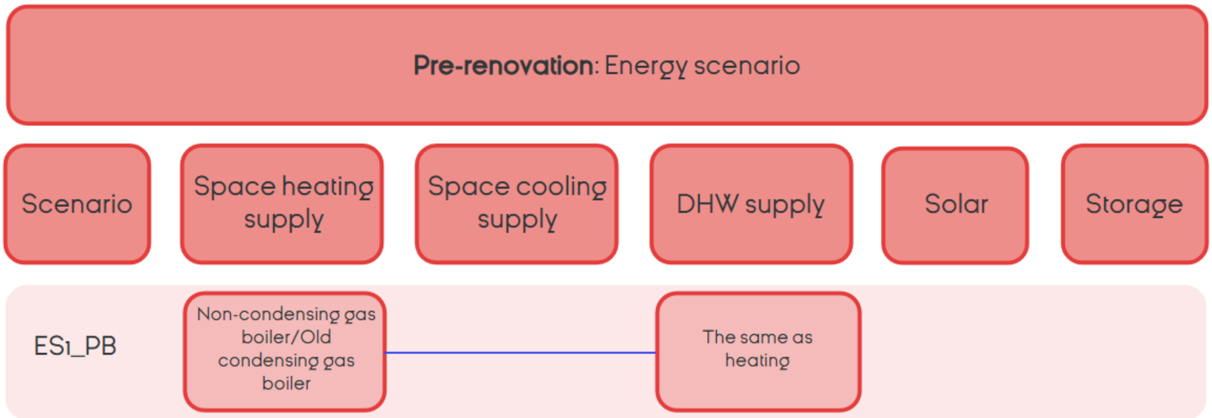

Figure 9. Proposed pre-renovation energy scenario for Italy.

ES1_PB Non-condensing/old condensing gas boiler

In Scenario ES1_PB, space heating is provided by a non-condensing or an old condensing gas boiler, representing a conventional and relatively inefficient technology. This same system is also used to supply domestic hot water (DHW), indicating a shared thermal source for both services. No systems are available for space cooling, solar energy and thermal storage.

Both centralised and apartment-based boilers are typical in Italy, but for pre-renovation scenario centralised boilers are proposed.

2.4.2. A Renovation Energy Supply Baseline Scenario

Based on case study buildings and interviews with local partners, a renovation baseline for Italy building archetype is proposed:

Heating

- Energy scenario 1, pre-renovation: Centralised new gas boiler
- Energy scenario 2, pre-renovation: District heating

Cooling

- Air-to-air heat pump system.

Domestic Hot Water

- Energy scenario 1, pre-renovation: Centralised new gas boiler (same as heating)
- Energy scenario 2, pre-renovation: District heating (same as heating)

Solar System

- No solar systems.

Storage

- No additional energy storage.

Figure 10 represents proposed renovation baselines for Italy building archetype.

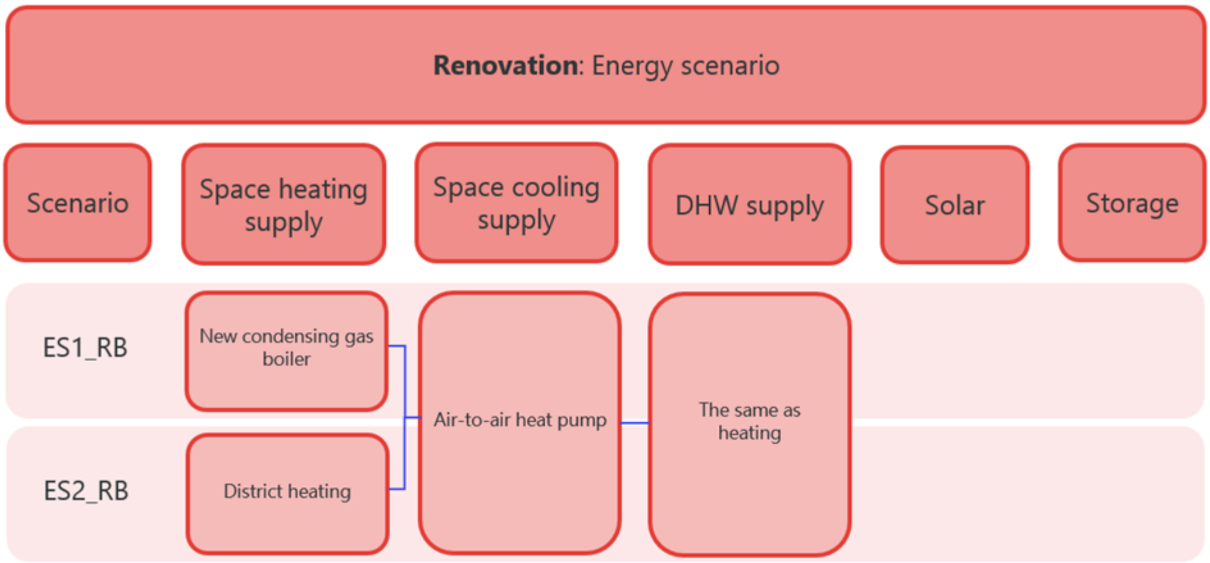

Figure 10. Proposed renovation energy scenario for Italy.

ES1_RB New condensing gas boiler, air-to-air heat pump

Space heating is supplied by a new condensing gas boiler and space cooling is provided through an air-to-air heat pump. The domestic hot water supply remains coupled with the space heating system, following the same configuration as the heating source. As in the pre-renovation stage, solar energy systems and storage solutions are not implemented or explicitly considered in these scenarios, suggesting a limited integration of renewable or auxiliary energy sources at this stage of renovation.

ES2_RB New condensing gas boiler, air-to-air heat pump

A district heating network is utilized. A space cooling is provided through an air-to-air heat pump. The domestic hot water supply remains coupled with the space heating system, following the same configuration as the heating source. As in the pre-renovation stage, solar energy systems and storage solutions are not implemented or explicitly considered in these scenarios, suggesting a limited integration of renewable or auxiliary energy sources at this stage of renovation.

2.5. Conclusion

For baselines, Belgium, Estonia, and Italy rely mostly on gas for heating. However, in Estonia and Italy, district heating could be an option in renovation baseline scenarios. In Norway, electric heaters and wood burning stoves are typical for heating. The domestic hot water heat source generally follows the main heat source, although some variation between gas and electricity can be seen. When comparing pre-renovation scenarios (1990-2010) and renovation scenarios, there are still differences in the efficiencies of the systems, even though the energy source remains the same.

Gas

There are two different technologies: non-condensing and condensing gas boilers. Condensing gas boilers emerged in the market in the 1990s and became mainstream solutions during the 2000s-2010s, depending on the country.

Condensing gas boilers are a developed technology and can achieve higher efficiency than traditional gas boilers. The efficiency of gas boilers also reduces over their lifetime.

For gas boilers, there are two main methods to report efficiency:

- Higher Heating Value (HHV) / Gross Calorific Value (GCV): Considers the total heat energy produced by the combustion of a fuel, including the heat released when water vapour condenses to liquid.
- Lower Heating Value (LHV) / Net Calorific Value (NCV): Represents the heat released during combustion, excluding the heat of condensation of water vapour.

When comparing different gas boilers, it is important to use the same method. Table 1 provides estimates for old and new condensing and non-condensing gas boilers using HHV/GCV and LHV/NCV methods.

Boiler type	**Typical Efficiency (HHV/GCV)**	**Typical Efficiency (LHV/NCV)**
Old Non-Condensing Gas Boiler	60-80%	60-80%
Old Condensing Gas Boiler (20-30 years old)	75-85%	83-94%
New Condensing Gas Boiler	92-98%	101-108%

Table 1. Typical efficiencies of different gas boilers.

Electricity

For traditional electricity boilers, there is now new technology developed in the past decades that would have similar improvement in efficiency to that we see from gas boilers. However, old electricity boilers typically have lower efficiency compared to new boilers. This is because new boilers can have higher insulation, and old boiler insulation can become damaged during its lifetime.

The typical efficiency for new electric boilers is 95-99%, whereas for 20-30 years old electric boilers, it is 80-90%.

Electric heaters that emit heat directly from the heater to the room do not practically have efficiency losses, so the efficiency of these heaters can be considered 100% in all cases.

3. System Description

This chapter introduces different alternative renewable and residual energy sources and supply systems for buildings and neighbourhoods. Most of the systems are well-known and used in buildings. However, neighbourhood-level systems are not that common, even though the technology is known and used at the building level. There are also some innovative systems, such as heat recovery from attics and underground spaces, which are introduced in more detail in Deliverable 4.3 – Feasibility of heat recovery from unharvested local sources in heritage environments.

The purpose of this chapter is to provide a general technical description of different systems, to better evaluate constraints and opportunities, as well as to create longlists and shortlists introduced later in this report.

Systems in this report refer to single, standalone heat, cold, or electricity generating/storage technologies. Renewable and residual energy systems can serve as the main heat source for a building, such as a ground source heat pump. However, in some cases, renewable and residual energy systems only support the main heat source. For example, buildings heated using a gas boiler can reduce gas usage by integrating an air-to-air heat pump, but an air-to-air heat pump alone typically cannot provide heating for the entire building throughout the year, nor can it heat domestic hot water, especially in cold climates. The combination of multiple systems to create a complete idea on how to provide heating or cooling is referred to as concepts in this report. The same applies to building-level as well as neighbourhood-level systems and concepts.

Neighbourhood-level systems and small thermal heating network in this report refer to systems that create energy networks for a few to a few dozen buildings located next to each other to circulate, store, and utilise local renewable and residual energy sources. This should not be confused with district heating systems. District heating is a large system that connects up to tens of thousands of buildings around the city in one energy system and is typically operated by an energy company owned by the city. A general example of a neighbourhood-level energy system is illustrated in Figure 11.

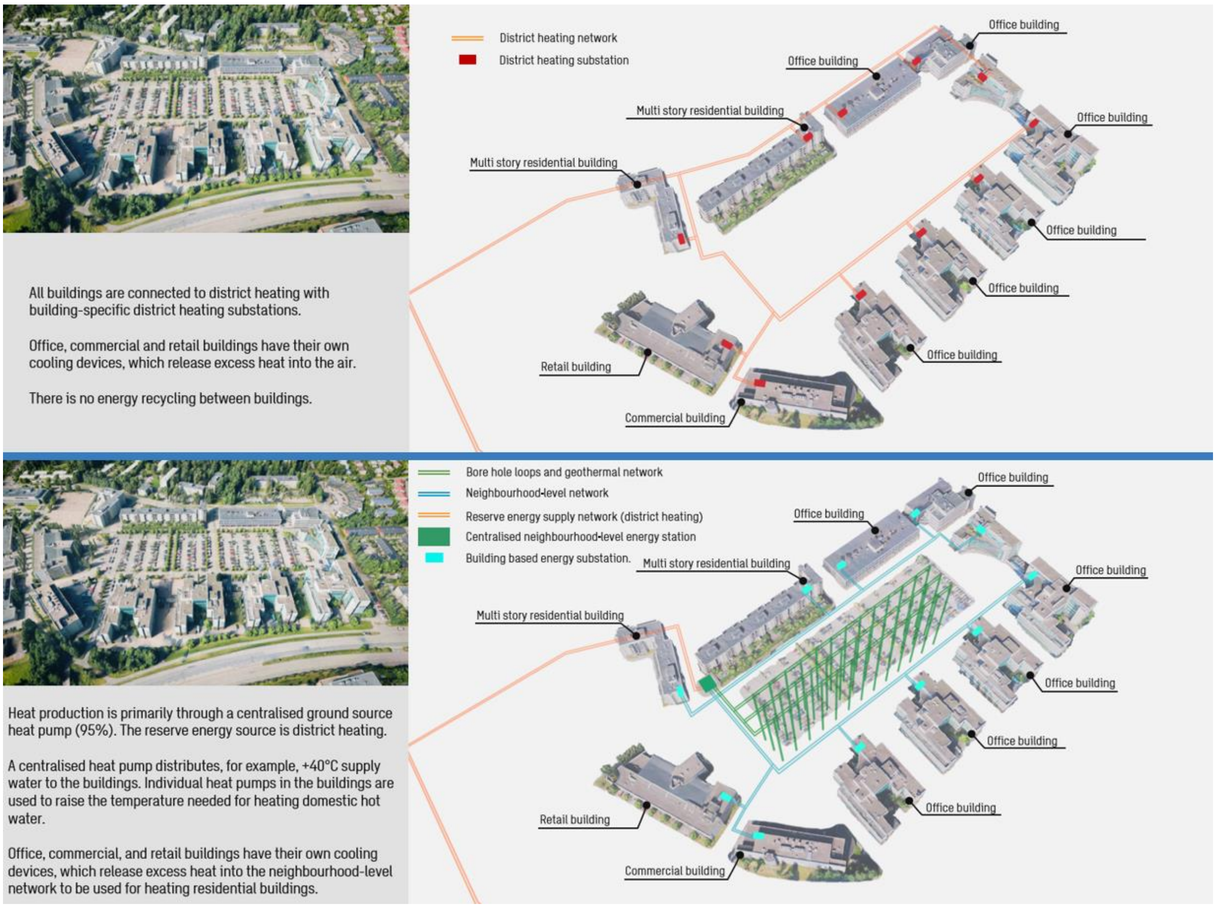

Figure 11: Above, all buildings are connected to a district heating network. Below, an example of a neighbourhood-level small thermal heating network system utilising geothermal energy and enabling the use of excess heat between buildings (Nöjd, 2024).

There are several alternatives for renewable and residual energy supply and production systems for individual buildings and neighbourhood-level systems. Descriptions of the technology, main components, as well as general guidelines on where the energy supply component can be installed and how, considering heritage and city centre layout aspects, are provided in Annex A: System Description.

A list of different building-level energy supply and production systems introduced in more detail in Annex A: System Description includes:

- Air-To-Air Heat Pump
- Air-To-Water Heat Pump
- Brine-Water Heat Pump
  - Ground Source Heat Pump
  - Water Source Heat Pump
  - Sewage Water Waste Heat
- District Heating
- Renewable Biomass
- Hydrogen Boiler
- Solar Thermal Collectors
- Photovoltaic-Thermal (PVT) Solar Panels
- Photovoltaic (PV) Solar Panels

- Building Integrated (BIPV) Solar Panels
- Water Buffer Tank
- Battery - Bi-Directional Charging of Electric Cars

A list of different neighbourhood-level energy production and supply systems introduced in Annex A: System Description includes:

- Air-To-Air Heat Pump
- Brine-Water Heat Pump
    - Ground Source Heat Pump
    - Water Source Heat Pump
    - Sewage Water Waste Heat
- Deep Geothermal Energy
- STC Field
- PV Field
- PVT Field
- Integrated Solar Collector
- Waste Heat Recovery
    - Industrial Heat
    - Datacentres
    - Commercial Refrigerators
    - Gathering Rooms
    - Large Underground Spaces
    - Attics
- Wind Energy
- Water Buffer Tank
- Hydrogen Fuel Cells

4. Constraints and Opportunities

When integrating renewable and residual energy systems into historic buildings and neighbourhoods, several aspects need to be considered. The need to safeguard the integrity of the historical city centre layout, as well as the morphology and traditional construction characteristics of historic buildings, makes it challenging to intervene in the consolidated urban heritage context. If a building is listed or part of the built heritage inventory, it means some of its structures, layout, or finishes are considered to be of special architectural, aesthetic, artistic, archaeological, social, or historical importance. With listed buildings, there is typically more detailed information available on which parts of the buildings are inherently linked to the building's heritage value. There are also technical aspects to consider. Integrating renewable and residual energy systems should not cause problems with noise levels, nor increase the risk of fire for buildings and neighbourhoods. Economic aspects are also important. If renewable or residual energy systems are very expensive to invest in and do not reduce annual energy costs significantly, they might be considered not feasible.

An interdisciplinary analysis was conducted to identify relevant constraints and opportunities for renewable and residual energy systems in the heritage context. Buildings and neighbourhoods were analysed together with technical and heritage experts at a workshop during a consortium meeting. Opportunities and constraints of each system at the building and neighbourhood level in the context of heritage protection, the city centre layout, and local climate conditions are summarised in a matrix, see Annex B: Constraints and Opportunities (Excel file). Table 2 summarises the aspects considered in Annex B: Constraints and Opportunities (Excel file).

Constraint and Opportunities	
Level	Building
	Neighborhood
Comment Type	Constraint
	Opportunity
Context	City centre layout
	Heritage
	Local climate conditions
Energy/Heat Source	Ambient
	Bedrock
	Burning of fuels
	etc…
Heat Pump	Air-to-air heat pump
	Air-to-water heat pump
	etc…
System	District heating
	PV
	etc…

Table 2: Aspects considered in Annex B: Constraints and Opportunities (Excel file).

Some general guidelines, not specific to any case study building or neighbourhood, have been identified and are introduced below. These have been prepared by technical experts and reviewed and commented on by heritage experts.

General Guidelines

City Centre Layout

- While considering heritage constraints and opportunities for renewable energy systems, the focus is mainly on the building envelope. This is because many renewable energy production and supply systems are integrated into the building envelope on the exterior of a building. On the other hand, some systems require major construction activities during installation but are not visible after construction. Geothermal energy and district heating are examples of such systems. Components that are installed inside a building, such as water buffer tanks, are typically located on the ground floor or in the basement, preferably in a secondary space such as a separate technical room if available.
- For components installed outdoors, consider installing only on façades that are not visible from the public domain, or in structures not directly connected to the building, such as outbuildings or sheds.
- For sloped roofs, install components only on the roof that is not visible from the public domain. With flat roofs or low-angled sloped roofs and tall buildings, the street-side roof can be considered if components are not visible from the public domain.

Heritage Value

- All interventions should entail a minimum impact on heritage values, both at the neighbourhood and individual building levels.
- Energy supply components are installed on the envelope and inside a technical room or other secondary space. Between the different components, piping and/or wiring needs to be provided. Piping and wiring are installed on the envelope structure either as surface mounting or embedded mounting. To protect the heritage value of the building structures, it is important that the installation is carried out with minimal impact on the valuable structures, elements, materials, and finishes. Chosen piping or wiring solutions should be suitable for room architectural solutions or surface finishing.
- Components, piping, and wiring should be installed so that they can be maintained and removed without impacting the valuable structures, elements, materials, and finishes.

Local Climate Conditions

- All renewable energy systems are applicable in all climate conditions.
- For cold climates, select systems that are suitable for operating in freezing temperatures.
- For cold climates, the removal of snow and the prevention of ice formation are important to consider while selecting the system.
- For warm and humid climates, systems need to be able to operate in hot and humid outdoor air conditions.

Each case study neighbourhood was analysed. The next sections will introduce the general guidelines for each neighbourhood.

4.1. Mild Climate - Belgium

The case study neighbourhoods of Ghent in Belgium are located in a mild climate. The buildings in the neighbourhood are mainly heritage masonry townhouses. A district heating network is available in the neighbourhood and a river is close by. Apart from residential buildings, the neighbourhood includes non-residential buildings, such as churches, underground parking, and office buildings.

City Centre Layout

- Energy supply components could be installed on façades that are not visible from the public domain or on annexes without heritage value.
- Buildings in the area are tightly packed together. When considering installing a heat pump outdoor unit, noise prevention is important.
- Roofs not visible from the public domain or annexes without heritage value could be ideal places for systems harnessing solar energy.
- Utilising geothermal heat is theoretically possible in the area, but limited plots, archaeological heritage value, and the status of listed buildings and plots make this very challenging. Specific circumstances such as the presence of archaeological patrimony in the soil, for example, the area around St Michael's Church containing remains of an ancient cemetery, make interventions in the soil more complex due to legislation for listed heritage.
- The nearby rivers are an ideal source of renewable energy. The water body could serve as a heat source without impacting the city centre layout after the construction work is complete. However, significant works need to be prepared for buildings not located next to the water body because the streets need to be opened to install piping.
- Excess heat from surrounding buildings, such as underground parking and office cooling systems, might be considered. This has minimal impact on the city centre layout if piping can be installed respecting the heritage values of the buildings and the surrounding area.
- Heat from attics could be harnessed, having minimal impact on the city centre layout if components and piping can be installed respecting the heritage values of the buildings and the surrounding area. When considering the attic of St Michael's Church, which is listed as a monument, the heritage values of the interior and subsoil should also be taken into consideration.

Heritage Value

- A building's envelope exterior impacts the city centre layout, and this impact was introduced above in general terms. However, if a building is listed or part of the ascertained built heritage inventory, there might be additional restrictions. Even structures, architectural elements, materials, or finishes not impacting the city layout might be considered to have heritage value. In this case, it might not be allowed to integrate a renewable energy system in or on this part of the building, even if it does not impact the city centre layout.
- Mounting piping and equipment, such as heat recovery systems from attics, should be done so that installations do not impact or have minimal impact on building structures, architectural elements, materials, or finishes considered to have heritage

value. It should also be considered that piping and systems can be maintained and removed easily without affecting parts with heritage value.

Local Climate Conditions

- While Belgium is located in a mild climate, there might be some quite cold periods as well as warm and humid periods. Selecting systems suitable for sub-zero conditions as well as warm and humid conditions is required.

Neighbourhoods

Belgium has two case study neighbourhoods, Sint-Michielsplein, Figure 12 and Vlaanderenstraat, Figure 13.

Figure 12: Map of the neighbourhood 'Sint-Michielsplein' in Ghent (Maton, 2024)

Identified potential renewable and residual energy sources but not limited to, in the neighbourhood of Sint-Michielsplein are:

Heating and Cooling

- River Leie.

- Underground parking.
- Geothermal energy.

Solar

- Harvesting energy from the attics.
- PV and solar collectors located on roofs not visible from the public domain. Outbuildings can also be considered.

Storages

- Underground parking.

Energy Circulation

- Different building types (office and residential) provide potential to utilise thermal energy within the neighbourhood. For example, excess heat from cooling office spaces could be used to pre-heat residential spaces or produce domestic hot water.

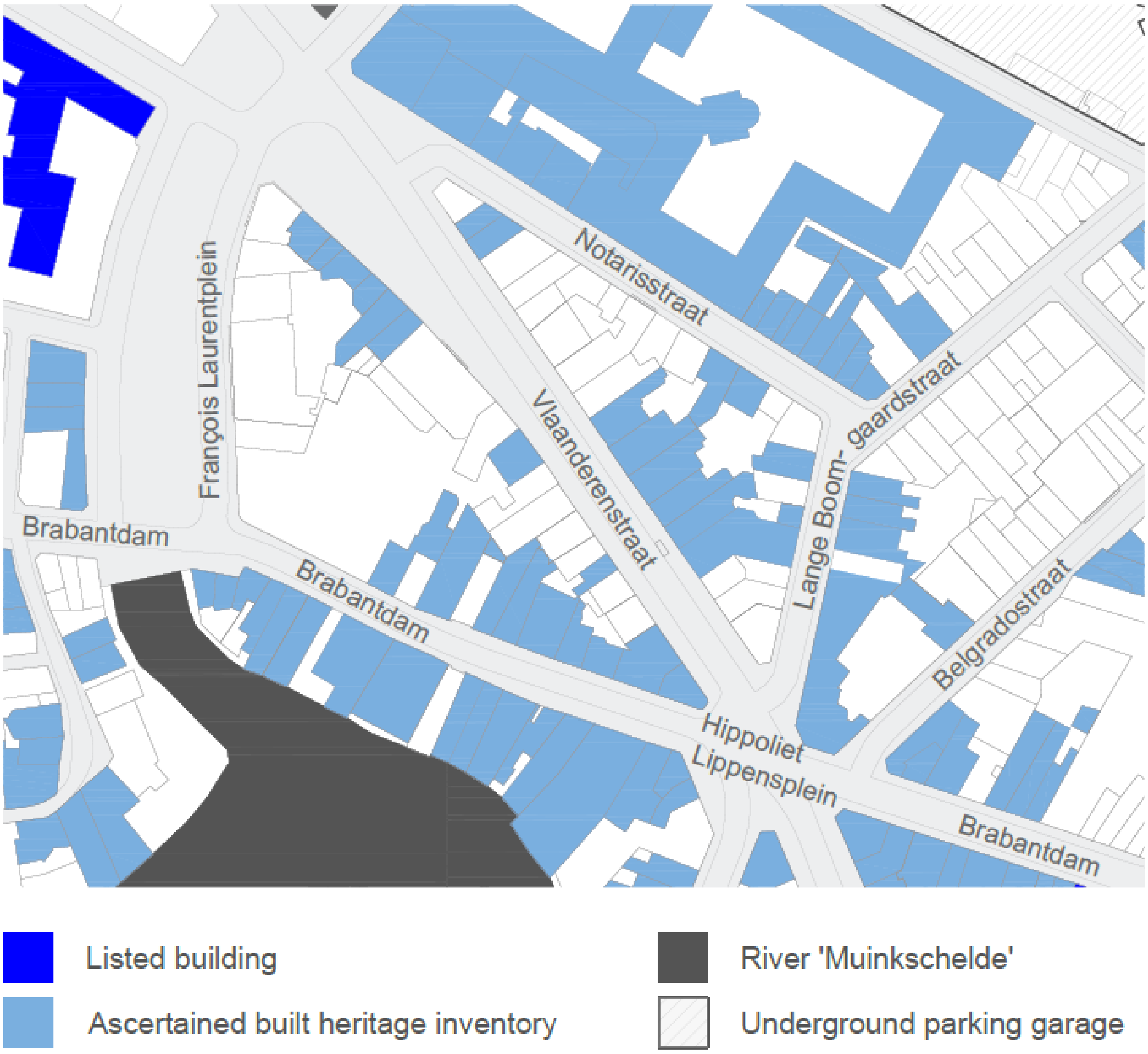

Figure 13: Map of the neighbourhood Vlaanderenstraat in Ghent (Maton, 2024)

Identified potential renewable and residual energy sources but not limited to, in the neighbourhood of Vlaanderenstraat are:

Heating and Cooling

- River Muinkschelde.
- Geothermal energy.
- Underground parking.
- District heating.

Solar

- Harvesting energy from the attics.
- PV and solar collectors located on an outbuilding without heritage value or on a non-visible sloped roof.

Storages

- Underground parking.

Energy Circulation

- Different building types (commercial and residential) provide potential to utilise thermal energy within the neighbourhood. For example, excess heat from cooling office spaces could be used to pre-heat residential spaces or produce domestic hot water.

4.2. Cold Climate - Norway

The case study neighbourhood of Bakklandet in Trondheim is located in a cold climate. There are many wooden buildings attached to each other. The buildings are situated throughout the Bakklandet neighbourhood. The River Nidelva flows adjacent to the area.

City centre layout

- Energy supply components could be installed on the side and rear façades so that they are not visible from the street. However, it is not desirable for these components to be visible from the River Nidelva, which needs to be considered for buildings located on the west side of the main street.
- Buildings in the area are tightly packed together, with very limited backyard spaces. When considering the installation of a heat pump outdoor unit, noise prevention is important.
- Roofs not visible from the main street and the River Nidelva could be equipped with systems harnessing solar energy.
- Utilising geothermal heat is possible in the area, but the limited plots make this very challenging. However, the street surfaces in the Bakklandet neighbourhood are not original. These streets could be utilised for geothermal heating without impacting the city centre layout.
- The River Nidelva is an ideal source for renewable energy. The river is already used as a heat source for neighbouring buildings and could serve as a heat source for buildings in Bakklandet without impacting the city centre layout.

Heritage value

- There are listed and non-listed buildings in the neighbourhood, and the buildings are wooden. When considering the installation of heat pump outdoor units, it is important to ensure that they do not damage the façade or envelope structures. Outdoor units cause draughts and change temperatures around the units. Additionally, outdoor units produce condensate water, requiring necessary protective elements and mounting systems to preserve the building façade and structures.
- Any installation might introduce damage to original materials and elements, both in terms of physical defects and harming the heritage values. Wooden structures, such as original panelled timber constructions, are more vulnerable and exposed to climate strain than plastered constructions.
- There are considerations/regulations linked to the neighbourhood level:
    - Consideration zone in the municipal area plan.
    - Conservation area in the zoning plan.
    - The municipal antiquarian emphasises the need for individual processing/discussions for each property.
    - The current municipal sector plan for cultural heritage and cultural environments states in § 10.2: "Buildings designated as having antiquarian value in class A, B, or C on the municipal 'Cultural Heritage Map' should be preserved. Roof shape, façades, windows and doors, choice of materials, and colours should be maintained in order to preserve the character of the buildings and structures."
    - Beyond this, there are no specific guidelines for the use of materials and the design of changes to heritage buildings in the neighbourhood.
- Since the buildings are wooden and attached to each other, special care needs to be taken for fire protection. Integrating electrical systems, such as PV panels, should be done with extra care.
- Buildings are mainly heated with wood-burning stoves and electric heaters. Using renewable energy systems that require a radiant network and emission systems will necessitate some refurbishment inside the buildings. Heritage values need to be considered, and installation needs to be done to ensure minimal or no harm is caused to the building structures.

Local climate conditions

- Although Trondheim is in a cold climate, the River Nidelva does not freeze during the winter, making it an ideal renewable heat source.
- Snow will reduce renewable energy generation from roof-mounted solar energy collectors and PV panels.
- Preventing ice formation from heat pump outdoor units is important. Condensate water management, such as condensed water drainage, is needed.
- Trondheim is located next to the Atlantic Ocean. Even though the neighbourhood of Bakklandet is not located right next to the sea, it is recommended that energy supply components should be suitable for high winds and seawater conditions.

Neighbourhood

The Norway case study neighbourhood, Bakklandet, located in Trondheim, can be seen in Figure 14.

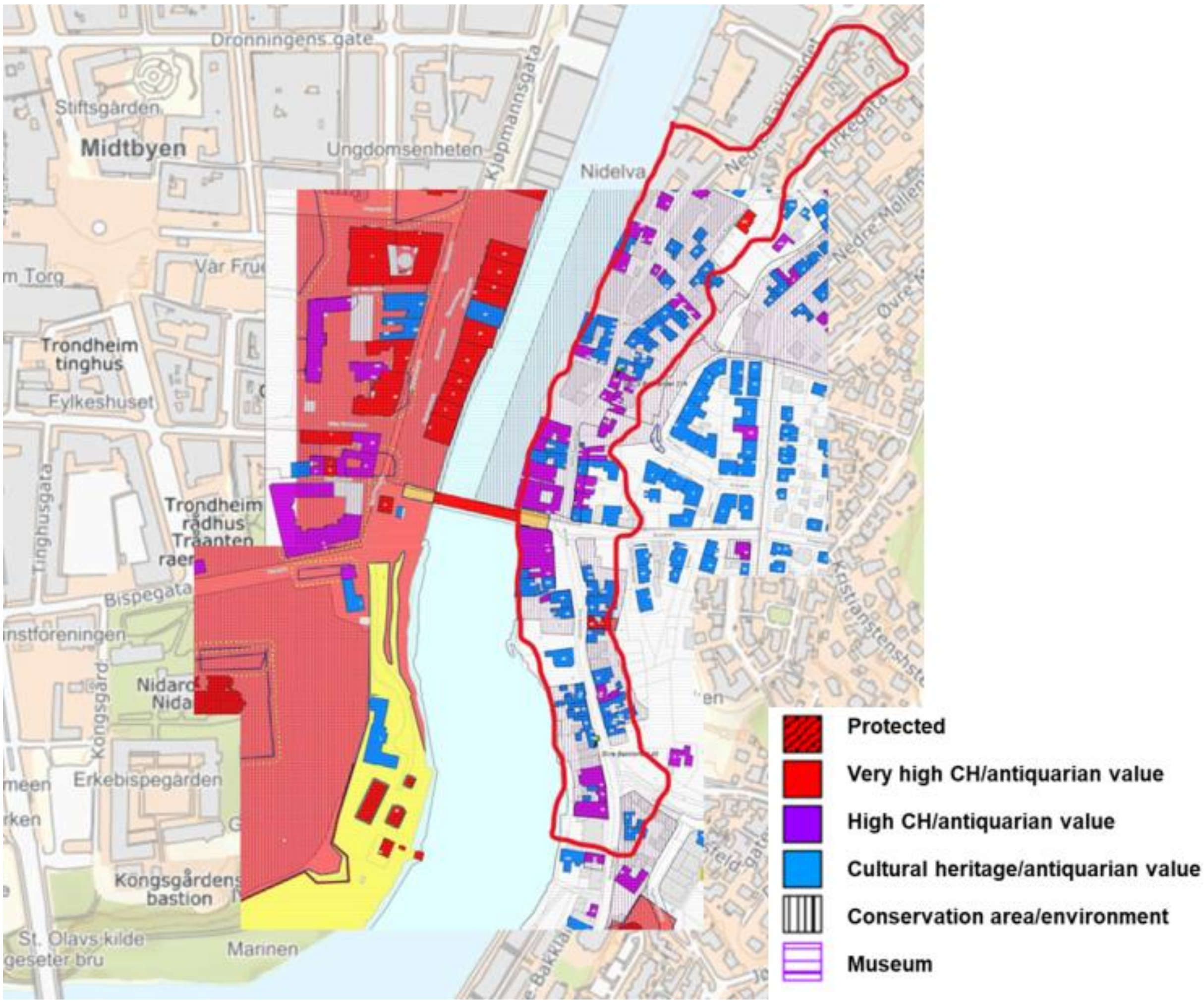

Figure 14: Map of the neighbourhood 'Bakklandet' in Trondheim (Trondheim municipality, 2024)

Identified potential renewable and residual energy sources, but not limited to, in the neighbourhood of Bakklandet are:

Heating and Cooling

- River Nidelva.
- District heating.
- Geothermal energy.

Solar

- PV and solar collectors located on roofs not visible from the public domain.

Storages

- None.

Energy Circulation

- Different building types (hotels, offices, and residential) provide the potential to utilise thermal energy within the neighbourhood. For example, excess heat from cooling in hotel and commercial buildings north of the neighbourhood could be circulated used to pre-heat residential spaces or produce domestic hot water.

4.3. Cold Climate - Estonia

The case study neighbourhood of Uus Maailm in Tallinn is located in a cold climate. There are mainly two archetype buildings in the area: wooden heritage townhouses and masonry heritage apartment buildings. A district heating network is available in the area.

City centre layout

- For wooden buildings, energy supply components could be installed on the side and rear façades so that they are not visible from the streets. The same applies to masonry buildings. However, masonry buildings are typically located so that there is free area for public domain around all façades, which makes it more difficult to find a location to install a renewable energy system without interfering with the city centre layout.
- Buildings in the area are loosely located in relation to each other. There are vast street, yard, and park areas between the buildings. This will help to prevent potential noise problems caused by heat pump outdoor units. Also, there is a lot of ground area to utilise for geothermal energy. This would not impact the city centre layout after the construction is complete.
- Buildings could be connected to the district heating network without interfering with the city centre layout after the construction works are complete.

Heritage value

- No specific constraints or opportunities. See generic comments.

Local climate conditions

- Selecting systems that are suitable for operating in subzero temperatures is required.
- Snow will reduce renewable energy generation from roof-mounted solar energy collectors and PV panels.
- Preventing ice formation from heat pump outdoor units is important. Condensate water management, such as condensed water drainage, is needed. It might not be allowed in Tallinn to install outdoor units on wooden façades due to condensed water problems and the risk of algae growth.

Neighbourhood

The Estonia case study neighbourhood, Uus-Maailm, located in Tallinn can be seen in Figure 15.

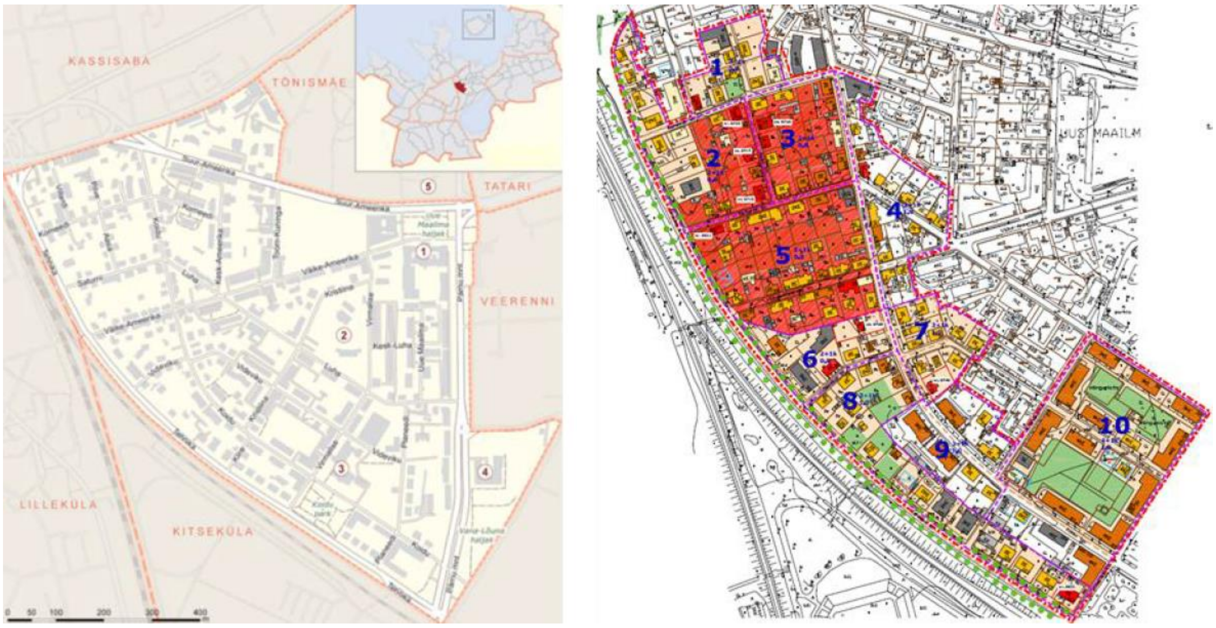

Figure 15: The area of Uus Maailm on a map of Tallinn (left) (Tallinna Linnaplaneerimise Amet, 2017) and the milieu-valuable area of Uus Maailm (right) (Tallinn, n.d.)

Identified potential renewable and residual energy sources, but not limited to, in the neighbourhood of Uus Maailm are:

Heating and Cooling

- District heating.
- Geothermal energy.

Solar

- PV and solar collectors located on roofs not visible from the public domain.

Storages

- None.

Energy Circulation

Different building types (commercial and residential) provide the potential to utilise thermal energy within the neighbourhood. For example, excess heat from cooling in commercial and retail buildings south of the neighbourhood could be used to preheat residential spaces or produce domestic hot water.

4.4. Warm Climate - Italy

The case study neighbourhood of Mantua in Italy is located in a warm climate. The buildings in the area are mainly heritage masonry buildings. A district heating network is available in the area. There is also a water body surrounding Mantua.

City centre layout

- Energy supply components could be installed on the side and rear façades so that they are not visible from the street side.

- Buildings in the area are tightly packed together, and backyard spaces are very limited. When considering installing a heat pump outdoor unit, noise prevention is important to consider.
- Roofs not visible from the main street could be ideal places to mount heat pump outdoor units and equip with systems harnessing solar energy.
- Utilising geothermal heat is theoretically possible in the area, but limited plots make this very challenging.
- The water body around Mantua is an ideal source for renewable energy. The water body could serve as a heat source without impacting the city centre layout after the construction work is complete. However, major works need to be prepared for buildings not located next to the water body because the streets need to be opened in order to install piping.
- There is also district heating available in the area. Buildings could be connected to the district heating network without interfering with the city centre layout after the construction works are complete.

Heritage value

- A building's external envelope impacts the city centre layout, and this impact was introduced above in general. However, if a building is listed, there might be some additional restrictions. For example, some external structures not impacting the city layout might be considered to have architectural and historical importance. In this case, it might not be allowed to integrate a renewable energy system in this part of the building, even if it does not have an impact on the city centre layout.

Local climate conditions

- Selecting systems that are suitable for operating in warm and humid conditions is required.

Neighbourhood

The Italian case study neighbourhood of Mantua can be seen in Figure 16 and Figure 17.

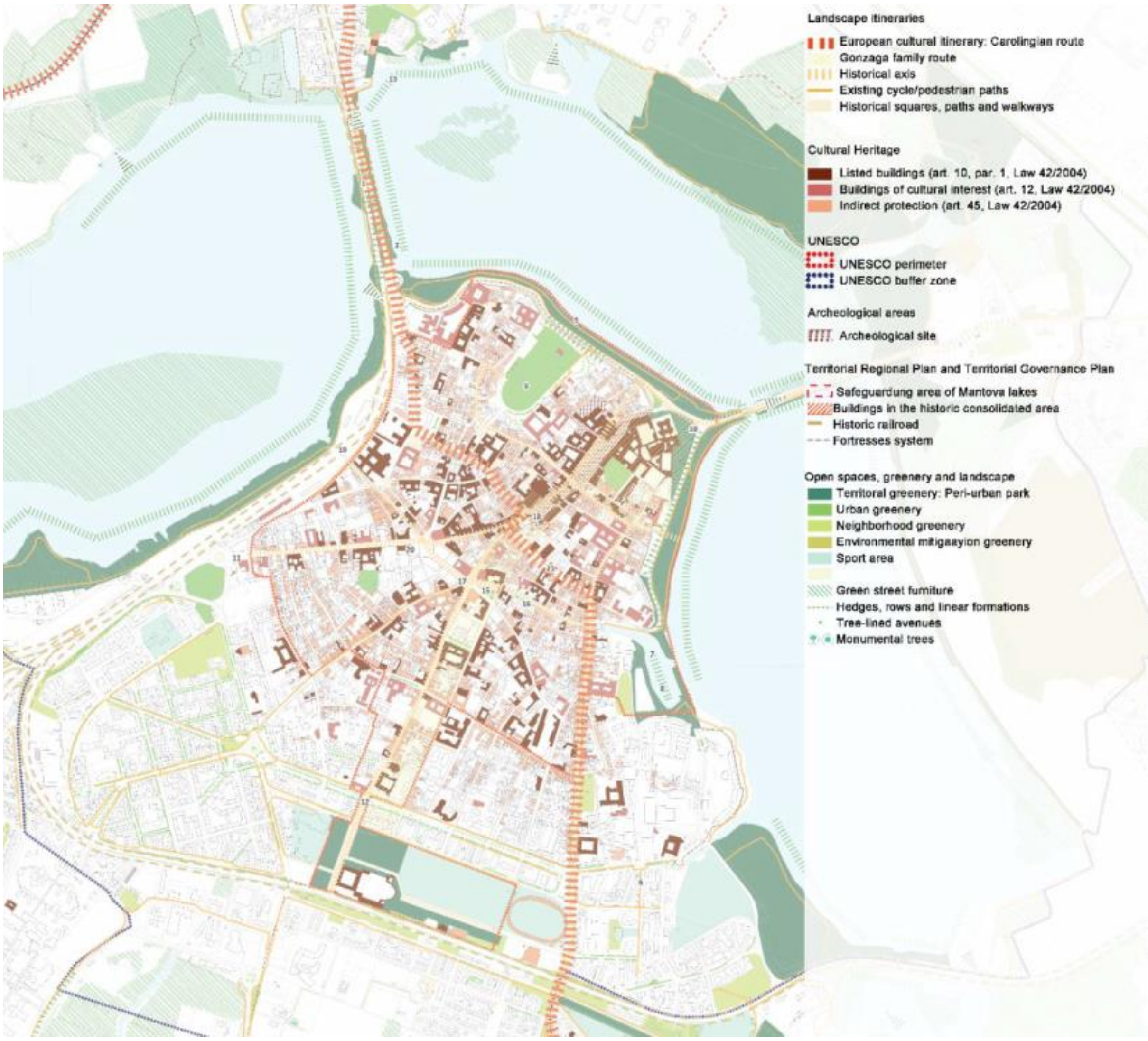

Figure 16: Extract from the PGT, indicating Mantua's old town and landscape (Comune di Mantova, 2022)

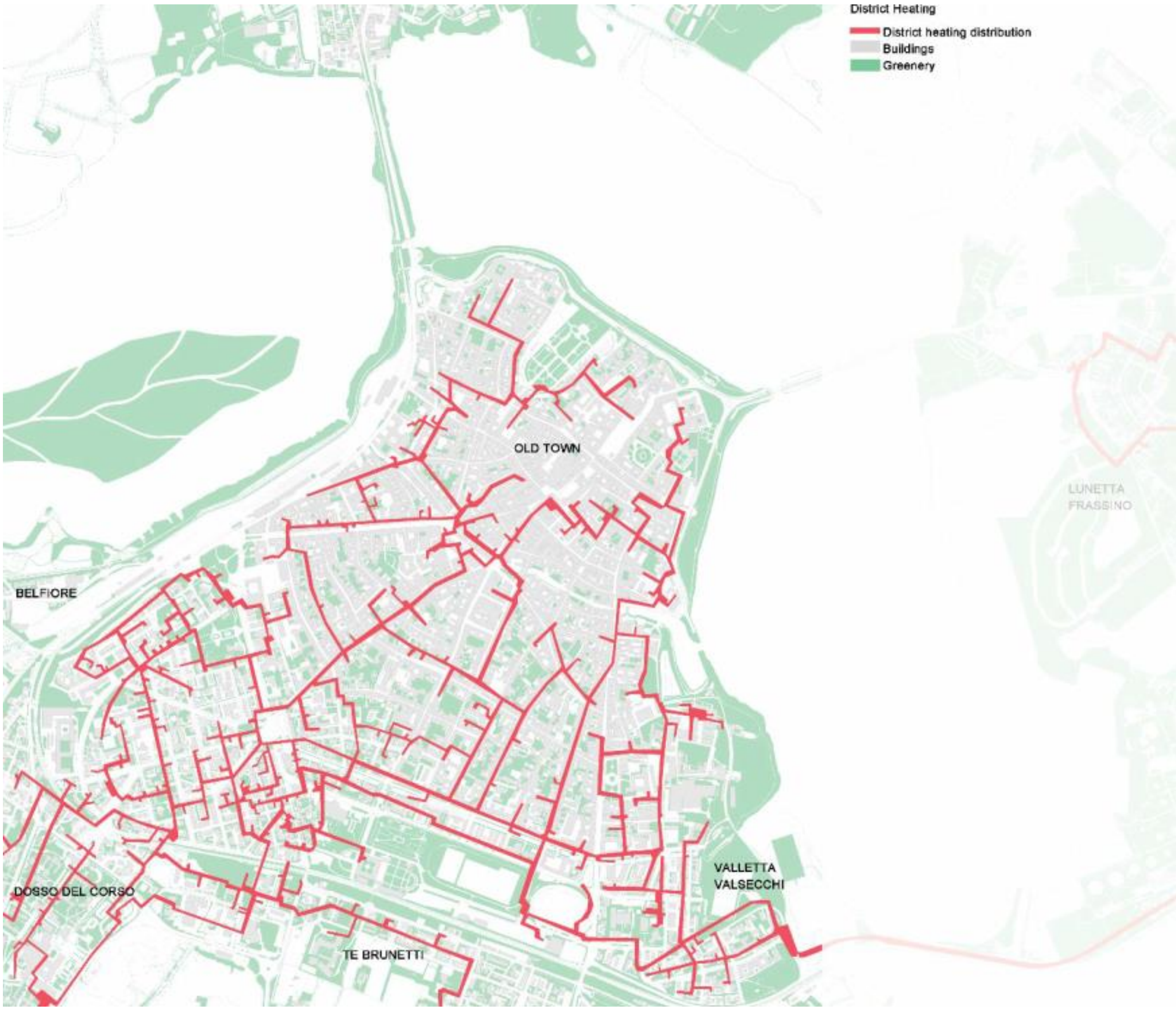

Figure 17: Mantua historical centre, district heating map (Buda, 2024)

Identified potential renewable and residual energy sources in the neighbourhood of Mantua include, but are not limited to:

Heating and Cooling

- District heating.
- Surrounding water body.

Solar

- PV and solar collectors located on roofs not visible from the public domain.

Storages

- None.

Energy Circulation

If different building types (commercial, office, and residential) can be identified close to each other, there is potential to utilise thermal energy within the neighbourhood.

5. Clean Energy Supply Concept Design for Individual Buildings

With the different opportunities and constraints regarding the known systems and the defined pre-renovation energy supply concept, several renovation supply concepts can be constructed. The first step in creating these concepts consists of listing a set of different systems, referred to as the longlist.

The second step in the process reduces this longlist to an intermediate list for each climate region, based on a scoring system. The objective of the intermediate list is to only retain the production systems that make sense in the historical city centre context. The final step reduces this intermediate list to a shortlist of different renovation supply concepts for individual buildings in each climate region.

The structure of the longlist in Work Package 4 (WP4) aligns as closely as possible with the structure of the Work Package 3 (WP3) longlist. Given that the WP4 longlists focus on concepts rather than on individual systems, notable differences exist between the WP3 and WP4 lists. Consequently, alternative criteria have been selected for the WP4 longlist. The opportunities and constraints identified in Chapter 4 serve as the foundation for a Table corresponding to each energy system, facilitating further evaluation.

5.1. Longlist of Systems

In Table 3, a long list is presented featuring various systems that can be implemented at the building level to provide sources for heating and cooling, generate electricity and/or heat through solar energy, and store heat and/or electricity. These systems were obtained through literature studies, discussions, and expert knowledge. The included systems have already proven their effectiveness in existing buildings. In this analysis, several innovative systems or sources were excluded as they still need to demonstrate their effectiveness sufficiently. The innovative systems will be included in Deliverable 4.3.

The energy systems have been categorised as follows:

- Production units: actively upgrading or generating heat
- Solar systems: using solar energy to produce heat or electricity
- Storage systems: for storing heat/cold or electricity

As hybrid solutions can be possible, no options are precluded at this stage. The objective of the longlist is to indicate possible and probable solutions for R²ES and to provide an initial assessment of the proposed systems. Sufficient flexibility is maintained to explore and identify interesting synergies between systems throughout the duration of the HeriTACE research project.

Energy Supply Systems Longlist – Building Level	
Production Units	Air-to-air Heat Pump
	Air-to-water Heat Pump
	Geothermal Heat Pump
	Open Water Heat Pump (Aquathermia)

	Waste Water Heat Pump (Riothermia)
	Heat pump connected to District heating network
	Renewable Biomass Boiler (solid)
	Renewable Biomass Boiler (liquid)
	Renewable Biomass Boiler (gaseous)
	Hydrogen Boiler
Solar Systems	STC-panels
	PVT-panels
	PV-panels
	BIPV (Building integrated PV)
Storage	Water Buffer Tank
	Battery - V2G
	(Hydrogen) Fuel Cells

Table 3: Energy systems longlist – building level.

This longlist serves as a starting point for each climate zone to construct a climate-specific intermediate list. During various project workshops, a scoring methodology was constructed to identify the best-performing systems based on several criteria. The intermediate list represents the application of the longlist to the specific climate zone boundary conditions. The intermediate list for each climate zone can be found in Annex C: Climate Specific Building Level Intermediate Lists. This intermediate list will be used to construct the different energy supply concepts for the Building Level Shortlist.

Scoring is conducted independently within each category (production units – solar systems – storage), ensuring that the intermediate list comprises the highest-scoring systems from all three distinct categories. The scoring relies on expert knowledge and involves multiple experts to encompass a broad spectrum of experiences. Scoring is conducted per climate zone due to differing heating and cooling demands.

The scoring system relies on three different criteria representing the major themes aligned with the desired definition of the baseline renovation concepts, thus influencing the outcomes of the HeriTACE project:

1. Feasibility
2. Sustainability
3. Heritage Value

The scoring system operates on a scale from 1 to 5, where 1 indicates poor performance, 3 signifies average performance, and 5 denotes excellent performance.

1. Feasibility

This criterion evaluates the likelihood of implementing the system within the given context. It is subdivided into the following aspects:

- Investment Costs: The financial implications of the system.
- Replicability and Versatility: The ease with which the technology can be applied and replicated in various project contexts, and the versatility of the technology itself.

- Regulatory Feasibility: The implications of heritage regulations and local urban planning guidelines; a lower score is assigned if regulations may hinder the implementation of the system.
- Energy Source Dependence: Limitations on production due to the intermittent nature of the energy source and/or external conditions affecting its availability.
- Maturity: The Technology Readiness Level of the proposed system.

2. Sustainability

This criterion looks at the broader picture and assesses the sustainability of the technology:

- Energy Efficiency: Evaluated not solely from an R²ES perspective; inappropriate solutions for densely populated urban centres (e.g., burning renewable biomass) are assessed accordingly.
- Acoustics: Measured in decibels (dB) for the system.
- Maintenance: The extent and cost of maintenance required.
- Material Use: An evaluation of the volume and nature of materials required, including the potential for recycling.
- Flexibility Enabler: The ability of the technology to interact with a higher-level grid.
- Climate Resilience: The technology's resilience to changing conditions, particularly concerning climate change, increasing temperatures, and reduced sunlight hours.

3. Heritage Value

This aspect is assessed in a subsequent phase and scored separately. This approach enables the longlist to serve as a more comprehensive tool for evaluating R²ES in both buildings and neighbourhoods within historic city centres:

- External Visual Impact
- Reversibility: The ease with which the system can be removed without affecting the building or neighbourhood.

Since the desired intermediate and shortlists are intended to provide an initial educated estimation rather than serve as an objective evaluation of the various solutions, no weighting of scores is applied. As previously mentioned, a trial-and-error approach is not excluded; interesting synergies may emerge at any stage in the process of defining the baseline renovation concepts.

5.2. Shortlist of Concepts: Cold Climate

When it comes to heat production units, if district heating from a renewable energy source is available, it should be utilised as this solution has the least impact on heritage value. When district heating is not available, traditional heat pumps (air-to-air, air-to-water, brine-to-water) are the best options for heating homes. Various systems are available to heat water fossil-free for domestic hot water (DHW): decentralised electric boilers, heat pump boilers, or air-to-water heat pumps.

All systems that utilise solar energy are included in the intermediate list. Although Building-Integrated Photovoltaics (BIPV) are generally less efficient than traditional PV modules, this technology is still considered due to its minimal impact on heritage value, and in some cases, it may be the only viable option for harnessing solar energy.

In cold climate zones, the intermediate list excludes aquathermia, riothermia, hydrogen boilers, batteries, and hydrogen fuel cells at the building level.

Aquathermia is not pursued further as it is rarely applicable to buildings; only a limited number of houses are located near rivers, making its use exceptional. Riothermia is also filtered out because the amount of heat it can provide would be insufficient to meet the full heating requirements as a standalone system. Consequently, the investment costs are too high compared to traditional heat pumps.

Riothermia and aquathermia are currently applied much less frequently than heat pumps that utilise air or ground sources. However, they could be advantageous in concepts where noise disturbance is a concern. Renewable biomass remains on the list, as it is a heating source that is already commonly used in colder climate zones.

The hydrogen boiler is not further investigated because it is generally more efficient to convert an energy source directly into heat at the building level. Hydrogen batteries are also not included in the intermediate list due to the inefficiency compared with home energy storage batteries.

5.2.1. Norway Heat, Cold and DHW Production & Storage Concepts

For the buildings in the Norwegian case study, it is important to note that they are typically heated with direct electric heaters and/or wood ovens. In some cases, there are no radiant heat distribution systems in the building. In such cases, implementing a heat production system that requires a radiant heat distribution system will necessitate building a new heat distribution system. This will increase the required investment and reduce the feasibility of investing in such systems. The indoor unit of a heat pump should be installed at ground level or in the attic, if present, as these buildings typically do not have basements.

Table 4 summarises the proposed concepts to be investigated in the Norwegian wooden log house archetype.

Energy Supply Concept	Production										Solar systems				Storage	
	Heat production for space heating				DHW production			Cold production for space cooling							Hot buffer	Cold buffer
	Air-to-air Heat Pump	Air-to-water Heat Pump	Brine-to-water Heat Pump	Aquathermia Heat Pump	Same as Heat Production	Decentral Electrical System	STC Boosted	Same as Heat Production	Air-to-air Heat Pump	No Cooling	PV-panels	STC-panels	PVT-panels	BIPV-panels	Water Buffer Tank	Water Buffer Tank
A: Split unit basic Cheapest option	X					X		X			X					
B: Split unit + BIPV Cheap and innovative solar	X					X		X			X			X		
C: Split unit +STC Solar thermal	X						X	X				X			X	
D: Split unit + PVT Elaborate solar	X						X	X					X		X	
E: ASHP Efficient air option		X			X					X	X				X	
F: GSHP, no cooling Geothermal basic			X		X					X	X				X	
G: GSHP with cooling Geothermal with cooling			X		X				X		X				X	
H: GSHP, no cooling + BIPV Geothermal, innovative solar			X		X					X	X			X	X	
I: GSHP, with cooling + BIPV Geothermal, air and solar			X		X				X		X			X	X	
J: Aquathermia + BIPV River and solar				X	X						X			X	X	

Table 4: Shortlist hot, cold and DHW production for Norway

Below is a brief description of each concept. For implementing each technology, the constraints and opportunities should be reviewed in Constraints and Opportunities.

A: Cheapest Option

This energy supply concept employs a basic air-to-air split-unit system that harnesses outdoor air as a heat source, distributing the generated heat inside the building via an air-based distribution system. PV panels are mounted where possible. Additionally, this system can provide cooling during the summer months. A decentralised electrical system is required to produce domestic hot water. While this solution represents the cheapest investment for utilising outdoor air thermal energy through heat pumps, it is important to note that it may not be the most efficient technology available.

B: Cheap and Innovative Solar

In addition to concept A, this concept also includes BIPV panels alongside standard PV panels.

C: Solar Thermal

Like concepts A and B, this energy supply concept employs a basic split-unit system.

Domestic hot water is heated using a centralised water buffer tank. Solar thermal collectors feed heat to the water buffer tank, which also includes an electric heating coil.

D: Elaborate Solar

This concept uses the same systems as concept C, but PVT panels are installed on the roof instead of STC panels, enabling local electricity generation in addition to thermal energy.

E: Efficient Air Option

This energy supply concept employs a system where heat production is provided using an individual air-to-water heat pump. Domestic hot water is also heated with the air-to-water heat pump.

F: Geothermal Basic

This energy supply concept employs a system where heat production is provided using an individual geothermal heat pump. Domestic hot water is also heated by the geothermal heat pump.

This concept won’t be feasible in many cases due to the limited outdoor area as mentioned in the constraints. For archetypes where area for boreholes is available to use geothermal energy, this concept can be favourable due to the higher efficiency of the system. No cooling is provided in this concept.

G: Geothermal with Cooling

This energy supply concept combines concepts A and F. Heating and domestic hot water are produced as in concept F, with a geothermal heat pump. Additionally, a basic split-unit system is added but only used for cooling during the summertime.

This concept increases indoor comfort compared to concept F with a cheap additional system. At the same time, it increases the annual energy consumption compared to concept F, because there was no active cooling at all in concept F.

H: Geothermal, Innovative Solar

This energy supply concept combines the basic geothermal system from concept F and the innovative solar system from concept B. Like concept F, this energy supply concept employs a geothermal heat pump for space heating and the heating of domestic hot water.

I: Geothermal, Air and Solar

This energy supply concept combines geothermal with cooling from concept G and the innovative solar system from concept B. Like concept G, this energy supply concept employs a geothermal heat pump for space heating and the heating of domestic hot water, and a basic split-unit system is added but only used for cooling during the summertime.

Traditional PV panels are installed on the rear slope of the roof, enabling local electricity generation without interrupting the heritage value of the cityscape. The production of local electricity generation will be increased by installing BIPV on the roof facing the street and riverside.

J: River and Solar

This concept is the same as concept I but utilises a river as a heat source instead of the underground. The aquathermia heat pump is used for space heating and the heating of domestic hot water. PV and BIPV panels are utilised for electricity production.

Only applicable for buildings located next to the river.

5.2.2. Estonia Heat, Cold and DHW Production & Storage Concepts

Table 5 summarises the proposed concepts to be investigated in the Estonian archetypes. No distinction is made for the archetypes, as the concepts themselves could potentially apply to both archetypes.

Energy Supply Concept	Production										Solar systems				Storage	
	Heat production for space heating				DHW production			Cold production for space cooling							Hot buffer	Cold buffer
	Air-to-air Heat Pump	Air Source Heat Pump	Ground Source Heat Pump	District Heating	Same as Heat Production	Decentral Electrical System	STC Boosted	Same as Heat Production	Air-to-air Heat Pump	No Cooling	PV-panels	STC-panels	PVT-panels	BIPV-panels	Water Buffer Tank	Water Buffer Tank
A: District heating Obvious option				X	X					X	X					
B: ASHP, no cooling Centralized air heat pump		X			X					X	X				X	
C: Air-to-air heat pump Cheapest option	X					X			X		X					
D: GSHP basic Geothermal basic			X		X					X	X				X	
E: DH + GSHP Geothermal combined DH			X	X	X					X	X				X	
F: DH + GSHP + cooling Geothermal with air cooling			X	X	X				X		X			X	X	
G: DH + ASHP + PVT Air heat and elaborate solar		X		X	X		X	X					X		X	X
H: DH + ASHP + BIPV Air heat and innovative solar		X		X	X			X						X	X	X
I: GSHP with cooling Geothermal with cooling			X		X			X			X				X	X
J: GSHP with cooling + BIPV Geothermal, cooling and solar			X		X			X						X	X	X

Table 5: shortlist hot, cold and DHW production for Estonia

Below is a brief description of each concept. For implementing each technology, the constraints and opportunities should be reviewed in Constraints and Opportunities.

A: Obvious Option

This energy supply concept connects the building to the local district heating network, when available, as in the case-study neighbourhood. The connection and substation of district heating for the building serve both space heating and domestic hot water. It is necessary to provide a hydraulic heat distribution and emission system in the building if there is none available beforehand.

PV panels are installed on the roof. To maintain the heritage value of the cityscape, PV panels might be considered for installation on roofs not visible from the public domain.

B: Centralized Air Heat Pump

In this energy supply concept, heat production is provided using a centralised air-to-water heat pump. Domestic hot water is also heated with an air-to-water heat pump.

C: Cheapest Option

This energy supply concept represents a scenario where heat production is provided using a decentralised air-to-air heat pump. Additionally, this system can provide cooling during the summer months. A decentralised electric or gas boilers are required to produce domestic hot water.

D: Geothermal Basic

In the Uus Maailm neighbourhood, there are lot of spaces between buildings. Areas for boreholes can be found, making geothermal an appealing alternative for Tallinn. In this concept, domestic hot water is also provided by the geothermal heat pump.

Extra electric heating needs to be added to the water buffer tank. This provides heat for space heating and domestic hot water only during the winter, when peak demands are highest. Peak demands typically occur for very short periods during the year, and boreholes are optimised based on energy use, not heat demand. The total electric connection power might need to be increased for the building.

E: Geothermal Combined DH

This energy supply concept is similar to concept D, but replaces the electric top-up heating with district heating during wintertime when peak demands are highest.

F: Geothermal with Air Cooling

For heating, this concept is similar to concept E. Geothermal heat is the main heat source for space heating and heating domestic hot water. District heating will support geothermal heating during the highest peak periods.

This concept also introduces decentralised air-to-air heat pumps for cooling purposes. In addition to typical PV panels, BIPV panels are introduced to maximise solar energy potential. Cooling during summer increases the demand for electricity, making maximum solar electricity necessary.

G: Air Heat and Elaborate Solar

Heat production in this concept is provided using a centralised air source heat pump. Domestic hot water is also heated with the air source heat pump for most of the year. PVT panels support the air source heat pump's heat production. Cooling can also be provided through the air source heat pump system.

District heating provides heat for space heating and domestic hot water only during the wintertime, when peak demands are highest. By using district heating to support peak heat demands, it is possible to reduce the number of water buffer tanks as well as allow the building to operate with a lower power (electric) connection.

PVT panels are installed on the roof's where not visible from public domain.

H: Air Heat and Innovative Solar

This concept is similar to concept G, but PVT panels are replaced by BIPV panels. Heat production is provided using a centralised air source heat pump. Domestic hot water is also heated with the air source heat pump for most of the year.

I: Geothermal with Cooling

This concept is similar to concept E, but with the implementation of cooling through the geothermal heat pump.

J: Geothermal, Cooling and Solar

This energy supply concept is similar to concept I, but BIPV panels are used instead of traditional PV panels.

5.3. Shortlist of Concepts: Mild Climate

The intermediate list for the mild climate zone, Annex C: Climate Specific Building Level Intermediate Lists, is similar to that of the cold climate zone, except for heating through renewable biomass, as this is less commonly used as the main heating system. Biomass is not readily available in urban contexts and requires delivery from external locations. This necessitates a continuous supply and storage, complicating practical usage. Additionally, the efficiency of biomass systems is significantly lower compared to traditional heat pumps.

The Belgian archetypes are often terraced houses, which means that access to any gardens or backyards is typically difficult. Although this is a practical problem at this moment in time, it might not be in the (near) future; thus, geothermal energy is still included at the individual building level due to its large potential.

The main focus for energy production systems in mild climate zones will be on heat pumps utilising air as an energy source. These systems can provide both heating and cooling for the building. The outdoor unit can be situated at the rear of the building, as this area generally holds less heritage value. The indoor unit should be installed in the basement or attic, both of which are almost always present. If both the basement and attic are occupied, this would result in a loss of space due to the mechanical room required for the system. The ASHP will be considered as the common renovation option and thus will have the most variations in the shortlist, allowing for proper comparison.

To produce domestic hot water (DHW), various systems are available to heat water fossil-free: decentralised electric boilers, heat pump boilers, or via the space heating heat pump system

In Belgium, there are generally few restrictions on the use of photovoltaic (PV) panels. Ideally, panels should be installed on the roof at the back of the building, provided this orientation is favourable for energy generation. If it is only advantageous to place PV panels on the front roof of the building, Building-Integrated Photovoltaics (BIPV) can be considered to preserve the historical value of the structure. Batteries to store the electrical energy produced by the solar panels are not included in the shortlist as the number of panels that could be installed is dependent on the roof area and orientation. If the simulations of the energy supply concepts show a significant surplus of solar energy compared with the building's energy consumption, the feasibility of batteries will be researched. The investment cost of batteries at this moment in time is mostly too expensive to be financially feasible. This could change in the future due to technological innovation and improvements.

Table 6 summarises the proposed concepts to be investigated in the Belgian archetypes. No distinction is made for the different archetypes as the concepts themselves could potentially apply to all archetypes. These concepts are selected from the intermediate list.

Energy Supply Concept	Production										Solar systems				Storage	
	Heat production for space heating				DHW production				Cold production for space cooling						Hot buffer	Cold buffer
	Air-to-air Heat Pump	Air Source Heat Pump	Ground Source Heat Pump	District Heating	Same as Heat Production	Decentral Electrical System	STC Boosted	PVT Boosted	Same as Heat Production	No Cooling	PV-panels	STC-panels	PVT-panels	BIPV-panels	Water Buffer Tank	Water Buffer Tank
A: Split-unit basic Cheapest option	X					X			X		X					
B: ASHP basic Common option		X				X			X		X					
C: ASHP + DHW Common option, DHW incl.		X			X				X		X				X	
D: ASHP + solar DHW Solar powered DHW		X					X		X		X	X			X	
E: ASHP + PVT Elaborate solar		X						X	X				X		X	
F: ASHP + BIPV Innovative solar		X			X				X					X	X	
G: ASHP + no roof area No roof available		X				X			X							
H: GSHP basic Common option expensive			X			X			X		X					
I: GSHP + STC regeneration Geothermy without cooling			X		X					X		X			X	
J: District heating basic Least impact on heritage				X	X					X	X				X	

Table 6: Shortlist hot, cold and DHW production for Belgium.

Below is a brief description of each concept. For implementing each technology, the constraints and opportunities should be reviewed in Constraints and Opportunities.

A: Cheapest Option

This energy supply concept uses a basic split-unit system to utilise the outdoor air as a heat source and distribute the heat through air inside the building. Therefore, new distribution systems are required. The air-to-air heat pump can also be used for cooling during the summer season. A decentralised electrical boiler is the easiest, and therefore the cheapest, option for domestic hot water. This system represents the cheapest way to use outdoor air as a heat source but is not the most efficient technology.

B: Common Option

This concept represents a scenario where the heat production, and possibly cold production, is provided using an individual air-to-water heat pump. Domestic hot water is produced by a decentralised system. This is a concept that would be frequently implemented in Belgian cities and can be seen as a common solution.

C: Common Option with DHW Included in the Space Heating Heat-Pump.

This concept is similar to concept B. Domestic hot water is also produced by the air-to-water heat pump.

D: Common Option with Solar Powered DHW

In this concept, the air-to-water heat pump is again used as the main heating system, which can also provide cooling during the summer season. In this case, the roof offers an opportunity to install solar thermal collector (STC) panels to provide the heat needed for DHW.

E: Common Option with PVT Panels

If the installation of PV panels or STC panels on the roof of a building is possible, the roof can also be used to install photovoltaic-thermal (PVT) panels. These panels are a combination of PV and STC panels and simultaneously produce electricity and heat for DHW. These panels are more expensive but have high efficiency and can be interesting for the future. These panels are combined with an air-to-water heat pump for heating and cooling.

F: Common Option with BIPV

If solar panels cannot be installed due to restrictions related to heritage value, BIPV panels on the roof or façade can be considered to harness solar energy. The main heating and cooling system is the same as in the previous concept.

G: Common Option When No Roof Area Is Available

In some cases, the orientation of the roof will not be favourable for installing solar panels. For example, when the back of the roof is north-facing and no PV panels can be placed on the front of the roof due to heritage value, or when shading would have a significant impact on solar energy production.

H: Ground-Source Heat-Pump Basic

Belgian cities often have row houses with a limited area of garden or outdoor space. This complicates the use of geothermal energy due to the practical difficulties of digging boreholes. For archetypes where it is possible to use geothermal energy, this concept can be favourable due to the higher efficiency of the system.

I: Ground-Source Heat-Pump with STC Regeneration

This concept would be an optimal technology when the installed heat delivery systems cannot be used for cooling as well, for example (low) temperature radiators. The heat produced by the STC panels can be used for the regeneration of the borefield in summer.

J: District-Heating Heat-Pump Basic

If a district heating system is available in the neighbourhood of the building, it can be beneficial to connect a water-to-water heat pump or heat exchanger depending on the temperatures of the district heating network.

5.4. Shortlist of Concepts: Warm Climate

In Mantua, the summers are warm and humid and the winters are cold, and it is partly cloudy throughout the year. Mantua is surrounded on three sides by artificial lakes receiving water from the River Mincio. In this regard, air-source heat pumps emerge as the most cost-effective solution. Their ability to provide both heating and cooling functions with high energy efficiency makes them well-suited to the moderate thermal demands of these regions. The initial investment in air-source heat pumps is often offset by their lower operational costs over time, contributing to economic and environmental advantages. This combination of efficiency and cost-effectiveness positions air-source heat pumps as a practical and sustainable choice for HVAC needs in warm climates. Geothermal heat pumps present a viable solution in concepts where external air-source units cannot be installed due to aesthetic or spatial constraints. These systems leverage the stable underground temperatures for efficient heating and cooling, eliminating the need for visible external components. This makes them particularly advantageous in areas with strict aesthetic regulations or architectural limitations. However, the implementation of geothermal systems may be impeded by regulatory hurdles. The installation process often requires extensive permitting due to the need for drilling and ground-loop installations, which can be subject to stringent local and environmental regulations. Despite these challenges, the long-term benefits, including higher energy efficiency and reduced visual impact, make geothermal heat pumps an appealing alternative in cases where external units are impractical or prohibited.

Similarly, groundwater heat pumps could be easily installed in Mantua, where a reliable and sufficiently deep aquifer is available. However, regulatory challenges, such as obtaining water extraction and reinjection permits, can add complexity to their implementation. Both solutions will struggle to maintain proper indoor temperatures if the building envelope allows substantial heat loss during winter and heat gain during summer. This inefficiency forces the heat pump to work harder, leading to higher energy consumption, reduced cost-effectiveness, and a shorter lifespan due to increased operational strain. Thus, heat pumps should be adopted if envelope insulation is also performed.

Generally, in Italy, the restrictions on the use of photovoltaic (PV) panels on the roofs of heritage buildings are quite stringent. For this reason, only BIPV should be considered when the roof area could be used for PV.

Table 7 summarises the proposed concepts to be investigated in the Italian masonry heritage archetypes. No distinction is made for the different archetypes as the concepts themselves could potentially apply to all archetypes. These concepts are selected from the intermediate list.

Energy Supply Concept	Production										Solar systems				Storage	
	Heat production for space heating				DHW production			Cold production for space cooling							Hot buffer	Cold buffer
	Air-to-air (fancoil) Heat Pump	Air Source Heat Pump	Ground Source Heat Pump	District Heating	Same as Heat Production	Decentral Electrical System	STC Boosted	Same as Heat Production	Air-to-air Heat Pump	Air Source Heat Pump	PV-panels	STC-panels	PVT-panels	BIPV-panels	Water Buffer Tank	Water Buffer Tank
A: GSHP No place available for outdoor unit			X		X			X						X	X	X
B: ASHP Place available for outdoor unit		X			X			X						X	X	X
C: District heating				X	X					X				X	X	X
D: Water loop fancoil units	X				X			X						X	X	X
E: ASHP without PV No usable roof area	X				X			X							X	X

Table 7: Shortlist hot, cold and DHW production for Italy

Below is a brief description of each concept. For implementing each technology, the constraints and opportunities should be reviewed in Constraints and Opportunities.

A: Ground Source Heat Pump

This represents a concept where there is no space to install the outdoor unit of an air-source heat pump. Heat and/or cold production is achieved using a geothermal heat pump.

B: Air Source Heat Pump

This concept represents a situation where space for installing an outdoor unit of an air-to-water heat pump is available. Based on the local historical context and boundary conditions, this solution seems to be the most favourable and commonly used when heating is provided in a fossil-free way under current conditions.

C: District Heating

This represents a concept where the building can be connected to the district heating network for the production of heat and domestic hot water, while the cooling demand is met by using an air-source heat pump.

D: Water Loop Fan Coil Units

This corresponds to the most advanced concept, where the existing distribution system can be replaced by water loop fan coil units (WLFCUs) that increase/decrease the temperature of the water pre-heated/cooled by a centralised heat pump.

E: Concept Without PV

This concept is the same as concept B but without the installation of PV panels. In some situations, homeowners may choose not to install PV panels if the yield would be lower due to shading or north-oriented roofs, or due to financial limitations. The additional advantages of solar panels can be demonstrated by comparing with concept B.

In this concept, an air-source heat pump is chosen for fossil-free heating, but the situation without PV panels is of course also possible when district heating or geothermal heat pumps are used as the main production systems.

6. Clean Energy Supply Concept Design for Building Blocks

In this chapter, the scope is expanded to the neighbourhood level to allow more elaborate systems, thereby leveraging the scale advantage of such systems. Small thermal heating network plays a key role in the concepts as it enables multi-household dimensioning of systems and opens the door to large sustainable and residual sources.

6.1. Methodology

A longlist of possible clean energy supply sources for building blocks at the neighbourhood level was created by an expert panel using their experience, knowledge, literature, and Sweco reference projects. Energy sources that have already proven their readiness and beneficial effects are included in the longlist, as well as promising systems that are expected to be used significantly more in the near future. The innovative energy supply sources will be researched in D4.3.

Energy supply concepts that cannot be used due to city centre boundaries or impact on heritage value are withdrawn in the shortlist, where (hybrid) concepts of these sources are listed. As the impact of the climate is deemed to be low, a general shortlist was created with concepts that can be implemented into a small thermal heating network and/or cooling network in each climate zone. There are some climate-specific considerations defined that need to be taken into account when developing a concept.

The small thermal heating network will be optimised into 4th and 5th generation small thermal heating network to improve energy efficiency and compatibility with modern systems and controls. A 4th generation small thermal heating network (4GDH) system involves low-temperature networks that operate around 40-70°C. These systems are designed to integrate renewable energy sources and operate efficiently with lower heat losses. 4GDH networks are optimised for modern, well-insulated buildings requiring lower-grade heat. A 5th generation small thermal heating and cooling (5GDHC) system is a next-gen network that employs ultra-low temperatures close to ambient levels (below 40°C). These systems use heat pumps and decentralised energy resources for both heating and cooling, enhancing energy efficiency and flexibility. Figure 18 illustrates different generation district heating networks.

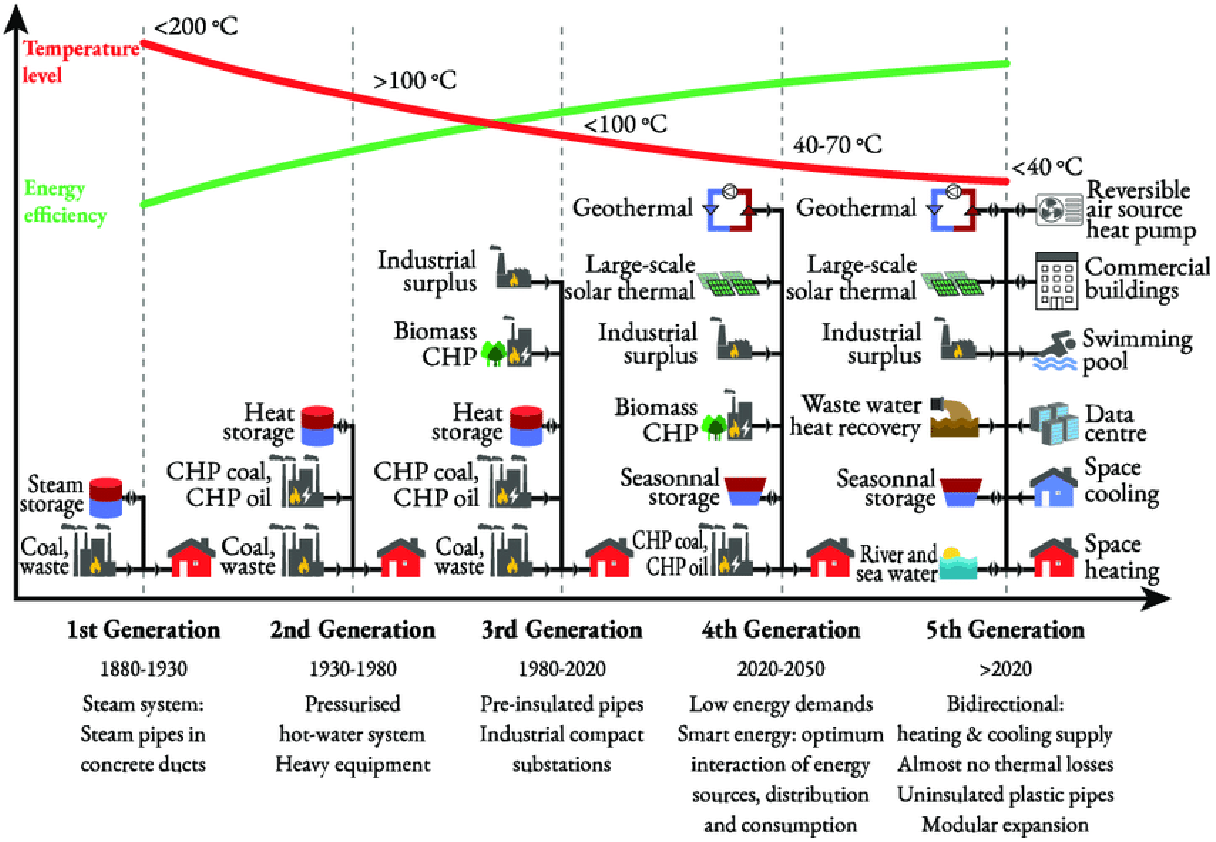

Figure 18: Illustration of different generation district heating networks (Abugabbara, 2021)

Several variations of the concepts in the shortlist can be explored, as storage and solar solutions are not predefined and will be parameters in the dynamic simulations in T4.5. Since small thermal heating network with temperatures lower than 40°C are possible, domestic hot water will need to be upgraded. Therefore, it will be provided at the building level to reduce pipe losses.

6.2. Longlist of Systems

Table 8 presents the longlist featuring various fossil-free energy supply concepts that can be implemented at the neighbourhood level for heating, cooling, generating electricity, and/or storage.

The energy systems have been categorised as follows:

- *Natural sources*: Energy sources that can be found in the natural environment.
- *Residual sources*: Energy sources that stem from man-made activities and are not used at this moment. Often, these are rest- or byproducts from another process.
- *Wind systems*: Systems that use wind energy to produce electricity.
- *Solar systems*: Systems that use solar energy to produce heat or electricity.
- *Storage systems:* Systems that facilitate thermal (heat/cold) or electricity storage.

Energy Supply Concepts Longlist – Neighbourhood Level	
Natural Sources	Aerothermal energy
	Geothermal energy
	Aquathermal energy

	Deep geothermal energy
Residual Sources	Energy recovery wastewater
	Energy recovery industry
	Energy recovery datacentres
	Energy recovery commercial (refrigerators)
	Energy recovery densely populated rooms
	Energy recovery waste burn
	Energy recovery large underground spaces
	Energy recovery attics
Wind Systems	Wind turbine
Solar Systems	STC field
	PV field
	PVT field
	Passive solar (playgrounds, roads, roof...)
Storage	Batteries
	Water buffer tank
	Hydrogen (fuel cells)

Table 8: Energy supply concepts longlist – neighbourhood level

All concepts in this longlist can be implemented in a neighbourhood in each climate zone, except for wind turbines, due to city centre boundaries.

When considering hybrid energy supply concepts, numerous combinations are possible, making an initial filtering of the energy supply concepts difficult. Therefore, the residual sources are grouped together as follows:

- *Low-temperature continuous heat source:* The residual systems in this category all operate at a low temperature but could provide a consistent heat flux. They are typically smaller, requiring some additional source to provide for a neighbourhood. Examples include heat recovery from wastewater, data centres, and commercial refrigerators.
- *High-temperature large-scale source recovery:* The residual systems in this category typically provide high temperature levels and large amounts of power, allowing them to suffice as a standalone system to provide for a neighbourhood. Examples include industrial heat recovery and waste incineration heat recovery.

The three remaining residual sources (densely populated rooms, large underground spaces, and attics) are somewhat innovative in the sense that they aren't widely applied, but since they utilise proven systems, they are included in this list. As their characteristics are different and they aren't widely applied, they won't be grouped together. Lastly, the solar and storage systems are subject to discussion in the simulations themselves, as they can vary widely throughout different neighbourhoods.

Reducing the intermediate list to four natural and five residual sources, and leaving solar and storage systems to be defined later in the simulations, the shortlist of concepts is created.

6.3. Shortlist of Concepts

Table 9 presents the shortlist of energy concepts for all climate zones. The first column in the table presents the name of the concept and uses numbering to indicate whether only natural sources, only residual sources, or both are used in a concept. Five concepts are created for when only natural sources are present, another five concepts constitute the hybrid concepts where both natural and residual sources are present, and only one concept will be further investigated when only residual sources are used.

The hybrid concepts that use the somewhat innovative residual sources do not yet specify the natural source, as this will be decided based on progressive insights and will follow from the simulation studies in T4.5. The type of small thermal heating network (generation level) is also named, as this summarises the temperature level and comfort provision. Additionally, sub-variations differentiating solar and storage systems are possible and will be the subject of detailed simulations.

One general shortlist of concepts is created for all climate zones. However, some concepts will not be simulated in T4.5 for specific climate zones, and there are minor climate-specific variations on how each concept is used. To indicate these differences, Table 10 accompanies the shortlist, showing which concepts will be simulated for each climate zone.

Concept Number	Residual Source	Natural Source	Small Thermal Network / District Heating Configuration
1.1 Reference case	-	ASHP	4GDHC
1.2 Reference geothermal	-	GSHP*	4GDHC/5GDHC
1.3 Hybrid naturals	-	ASHP + GSHP*	4GDHC
1.4 River source	-	WSHP (river)	4GDH/5GDH
1.5 Deep geothermal	-	Deep geothermal	3GDH
2.1 Low temperature continuous source recovery	Datacentre, wastewater or commercial heat recovery (WSHP)	GSHP*	4GDHC/5GDHC
2.2 Low temperature continuous source recovery	Datacentre, wastewater or commercial heat recovery (WSHP)	WSHP (river)	4GDH/5GDH
2.3+ Large historical building recovery	Attics (ASHP)	GSHP* or WSHP (river)	4GDH/5GDH
2.4+ Office & event function recovery	Densely populated rooms (ASHP)	GSHP* or WSHP (river)	4GDH/5GDH
2.5+ Air sourced geothermal recovery	Large underground spaces (ASHP)	GSHP* or WSHP (river)	4GDHC/5GDHC
3.1 High temperature large-scale source recovery	Industrial- or waste burn heat recovery	-	3GDH/4GDH

Sub variations possible for DHW production / storage /solar systems (next level of detail) for al concepts

GSHP*: a GSHP will always be combined with PVT panels to allow a smaller and more efficient borefield

concept+: innovative residuals that might need more elaborate simulations

4GDHC = 4th generation small thermal network / district heating & cooling: central HP
5GDHC = 5th generation small thermal network / district heating & cooling: decentral HPs

Table 9: Neighbourhood level shortlist concepts

Concept Number	BE	EST	IT	NO
1.1 Reference case	X	X	X	X
1.2 Reference geothermal	X	X	X	X
1.3 Hybrid naturals	X	X	X	X
1.4 River source	X		X	X
1.5 Innovative geothermal	X	X	X	X
2.1 Low temperature continuous source recovery	X	X	X	X
2.2 Low temperature continuous source recovery	X	X	X	X
2.3+ Large historical building recovery	X			
2.4+ Office & event function recovery	X	X	X	X
2.5+ Air sourced geothermal recovery	X	X	X	
3.1 High temperature large-scale source recovery	X	X	X	X

Table 10: Table indicating the occurrence of a concept in a climate zone

6.3.1. Reference Case (1.1)

This energy supply concept utilises a central air-source heat pump to extract heat from outdoor air and subsequently uses a small thermal heating network to distribute the upgraded heat to different buildings. The system is designed to operate without decentralised heat pumps for space heating, as all heat is generated by the central heat pump. During the summer season, the system can also provide cooling by reversing the working principle of the central heat pump. In this case, the small thermal heating network configuration is of the 4th generation.

Noise from outdoor units might be problematic in densely populated or historic areas, and high humidity can reduce the lifespan of outdoor units unless adequately maintained.

Specific Considerations for Norway (Cold Climate)
In Norway, a limitation of this system is that the peak heat demand can be remarkably high during the winter when the outdoor air is well below zero. High electric power is needed to back up the system during the coldest periods of the year. However, the peak demand can be partially reduced through the use of a model-predictive controller in combination with the storage of thermal mass.

Specific Considerations for Estonia (Cold Climate)
Similar to Norway, the energy supply concept in Estonia faces limitations during peak heat demand due to very cold outdoor air.

Specific Considerations for Belgium (Mild Climate)
In Belgium, this system represents the most basic and cheapest way to collectively provide a small neighbourhood with heating and cooling comfort.

Specific Considerations for Italy (Warm Climate)
In Mantua, Italy, this energy supply concept is widely available, easy to install, and suitable for retrofitting existing buildings. It is quite effective during mild autumns and springs but can face reduced efficiency during cold and humid winters.

6.3.2. Reference Geothermy (1.2)

This energy supply concept utilises a central ground source heat pump to extract heat from the earth and subsequently employs a district heating network to distribute the upgraded heat to various buildings. The district heating system can be of the 4th or 5th generation. This system must provide cooling during the summer months to maintain the thermal balance of the ground. If no cooling is provided, other ways of restoring the thermal balance of the underground will be needed for the system to work properly. PVT panels can be used for borefield regeneration, thereby reducing the size of the borefield.

Geothermy requires significant ground space, which might be challenging in urban areas or under historical preservation constraints. This has limited feasibility in densely built environments or areas with complex subsurface geology, and regulatory permissions might be required for drilling.

The current drilling techniques are expensive and require large machinery, which limits the roll-out of these systems in city centres. The scale advantage of a neighbourhood plays an important role in making geothermal systems financially feasible. As more emphasis is put on renewable sources, better drilling techniques and smaller machines are expected, both of which would leverage geothermal solutions in city contexts. Following this prognosis, geothermy will become a very important source, leading to its inclusion in many of the concepts here mentioned.

The addition of PVT panels will be present in every geothermal system in all concepts. This idea was proven for the Belgian reference case by other research projects, such as the SEEDs project. The PVT panels will solely be used in synergy with the borefield, not for domestic hot water production in households.

Specific Considerations for Norway (Cold Climate)
A typical neighbourhood in Norway is likely, although not guaranteed, to have some space available for a borefield, making this concept more interesting at the neighbourhood level compared to the building level, since the garden area of individual houses is limited.

Specific Considerations for Estonia (Cold Climate)
A typical neighbourhood in Estonia is likely, although not guaranteed, to have some space available for a borefield, making this concept more interesting at the neighbourhood level compared to the building level.

Specific Considerations for Belgium (Mild Climate)
In current conditions, geothermy at the building level is difficult due to limited access to the gardens in row houses. Using geothermal energy at the neighbourhood level would be the preferable option.

Specific Considerations for Italy (Warm Climate)
This energy supply concept is highly efficient, less affected by external weather conditions in comparison to an air-source heat pump, and able to provide stable heating and cooling suitable for Mantua's temperature variations.

6.3.3. Hybrid Naturals (1.3)

This energy supply concept integrates a central air-source heat pump and a ground-source heat pump to optimise heat extraction from both outdoor air and the earth. In this way, the concept exploits the high efficiency of the geothermal system while using the air system for peak demand, allowing a downscale of the more expensive geothermal system, thus creating cost benefits. The small thermal heating network will be of the 4th generation.

In this hybrid system, the air-source heat pump can provide additional heat during milder weather conditions, while the ground-source heat pump can effectively deliver consistent heating during colder periods. The system will also offer cooling during the summer months by reversing the operation of both heat pumps.

Specific Considerations for Norway (Cold Climate)
No specific considerations for this climate zone.
Specific Considerations for Estonia (Cold Climate)
No specific considerations for this climate zone.
Specific Considerations for Belgium (Mild Climate)
This method is widely applied in Belgium but requires space for a geothermal system, prohibiting it from being the reference case.

Specific Considerations for Italy (Warm Climate)
High reliability across all seasons allows these systems to adapt well to Mantua's winter fogs and summer heatwaves.

6.3.4. River Source (1.4)

This energy supply concept employs a central water-source heat pump that extracts heat from a nearby river. An aquathermal system, as it is frequently called, reaches the same high heating efficiencies as a geothermal system, making it an interesting source. It does not require thermal energy balance as water is continuously passing by, comparable to ambient air. Moreover, a river-source concept will not be used for cooling purposes as this causes river temperatures to rise, which should be avoided. The small thermal heating network will thus be of the 4th or 5th generation but solely used for heating.

The downside, however, is the low availability of river sources close to neighbourhoods, making this option very location-dependent.

Specific Considerations for Norway (Cold Climate)
This energy supply concept employs a central water-source heat pump that extracts heat from the river Nidelva located next to the case study neighbourhood.

Specific Considerations for Estonia (Cold Climate)
No river sources are available in the case study neighbourhood in Estonia.

Specific Considerations for Belgium (Mild Climate)
In Belgium, rivers were typically put underground to make space for roads and buildings, making them less accessible. In recent years, however, rivers have been re-opened to evacuate heat from the city and this trend is likely to continue, lowering the threshold of accessibility. A second obstacle in Belgium, often the largest hurdle to installing an aquathermal system, is legislation and obtaining the right permits, as aquathermia is often linked to disturbance of marine life, although, when installed correctly, this is not the case. With local politics becoming more aware of the issues, this barrier is expected to be removed or at least reduced.

Specific Considerations for Italy (Warm Climate)
This energy supply concept leverages Mantua's proximity to rivers (e.g., River Mincio) for efficient thermal exchange with high efficiency in heating modes. These systems are

dependent on water availability and quality, which may vary seasonally. They are subject to potential environmental concerns regarding river ecosystem impacts. Regulatory challenges for accessing and utilising river water make them difficult to realise; moreover, the infrastructure installation might be limited by local environmental protection policies.

6.3.5. Deep Geothermal (1.5)

This energy supply concept uses deep geothermal heat production as a direct source to heat various buildings. The high temperatures extracted from deep underground eliminate the need for a heat pump. Heat is distributed through a 3rd generation district or neighbourhood heating network. Cooling can be achieved with a heat pump or a chiller that elevates the extracted heat to higher temperature levels than the deep underground, allowing the heat to flow back into the ground. Deep geothermal systems provide high efficiencies for heating but come with high drilling costs.

Deep geothermal systems are considered to become financially viable when the heat demand is in the order of multiple 10 GWh, making them cost-effective for large neighbourhoods. Despite high drilling costs, they offer high heating efficiencies, and due to their potential and future developments, they are included in the list of viable energy supply concepts.

Specific Considerations for Norway (Cold Climate)
In Norway, deep geothermal systems can be used to supply heat to buildings with minimal or no use of heat pumps, provided the temperatures extracted are sufficiently high. However, currently there are no deep geothermal plants operating in Norway.

Specific Considerations for Estonia (Cold Climate)
The same considerations as for Norway are applicable.

Specific Considerations for Belgium (Mild Climate)
Permits are required to demonstrate that deep geothermal drilling will not result in earthquakes.

Specific Considerations for Italy (Warm Climate)
Currently, there are no deep geothermal systems in Italy.

6.3.6. Low Temperature Continuous Source Recovery (2.1 & 2.2)

This energy concept utilises residual heat from low-temperature continuous heat sources, such as wastewater, data centres, and commercial refrigeration stations. These sources provide energy for heating and cooling through typical heat pump systems, either air source or water source, which upgrade the residual heat and deliver it to district or neighbourhood heating networks. A natural source, such as geothermal or aquathermia, is always added to guarantee thermal comfort and cooling.

This concept can be designed as 4th or 5th generation district or neighbourhood heating network depending on the temperature levels of the sources.

Leveraging residual heat from wastewater requires close proximity to wastewater sources or treatment plants and may involve extensive and expensive retrofitting of sewer systems. Residual heat from data centres and commercial refrigeration stations provides significant potential due to the fast-growing demand for data centres and accompanying cooling.

However, large centres are typically located outside city centres, requiring large pipes or smaller connected centres to bring heat inside.

The hybrid nature of this system ensures effective low-temperature recovery, meeting the energy demands of various facilities sustainably.

Specific Considerations for Norway (Cold Climate)
In Norway, the demand for data centres and refrigeration systems is fast-growing, making residual heat recovery highly viable. Connecting data centres to city-level district heating in Norway is more suitable for bigger excess heat.

Specific Considerations for Estonia (Cold Climate)
Similar to Norway, Estonia leverages residual heat from data centres and commercial refrigeration stations effectively. The rising need for data storage and refrigeration indicates this type of heat recovery will play a key role in Estonia.

Specific Considerations for Belgium (Mild Climate)
In Belgium, sewage heat recovery is an upcoming, although mature, technology with its largest drawback being the availability of sewage canals with sufficient flow rate. The closer to the water treatment station, the higher the flow rates, suggesting limited potential inside city centres in most places. Residual heat from data centres and commercial refrigeration stations is often not used in Belgium, highlighting the untapped potential.

Specific Considerations for Italy (Warm Climate)
The city of Mantua lacks sufficient continuous low-temperature heat sources like data centres and commercial refrigeration stations, so the applicability of these systems could be limited, requiring additional investments to integrate with district heating networks.

6.3.7. Large Historical Building Recovery (2.3)

This concept represents an innovative approach to air-sourced heating. It utilises the air inside historic attics that reaches higher temperature levels compared to ambient air temperatures due to the solar irradiation on the typical black historic tiled roofs. Through a typical air source heat pump, this system captures and upgrades residual heat to supply a district or neighbourhood heating network. As with previous concepts, a natural heat source, such as geothermal energy or aquathermia, is integrated to ensure consistent thermal comfort and cooling, which is especially needed due to the volatile nature of the heat source.

This type of heat recovery has significant potential as it resembles a typical air source heat pump setup surrounded by a source with enhanced temperature levels.

This concept is not yet mature, making it a very innovative, although promising, addition to the list of concepts. Belgian city centres often contain large heritage buildings with black-tiled roofs and significant attics that can be exploited. The feasibility will first be researched in Belgian cases and could be further implemented in other climate zones if feasible.

Both 4th and 5th generation networks are feasible with this system. For cooling applications, using the ambient air as a heat sink seems more attractive than using church attics.

6.3.8. Office & Event Function Recovery (2.4)

The heating and cooling system for heritage buildings leverages the energy produced in areas with high occupancy, such as offices and event spaces. These areas often require cooling when people gather, generating residual heat that can be captured. This residual heat can then be upgraded using heat pumps, which vary depending on the type of cooling system used. The upgraded heat can be redistributed for heating residential spaces, providing an innovative solution that balances both heating and cooling needs. Additionally, natural heat sources such as geothermal or aquathermia are incorporated to ensure a stable supply of thermal comfort and cooling.

The performance of this system depends on building usage patterns, and retrofitting potential must be evaluated, particularly for heritage buildings. Regulatory hurdles may also need to be considered.

Specific Considerations for Norway (Cold Climate)
Norway's neighbourhoods have buildings with office and event functions that create opportunities for heat recovery. The concept is still innovative but can be easily rolled out.

Specific Considerations for Estonia (Cold Climate)
Like Norway, Estonia's neighbourhoods can exploit volatile energy sources from office and event spaces for heat recovery.

Specific Considerations for Belgium (Mild Climate)
There are no specific restrictions for this concept that should be considered.

Specific Considerations for Italy (Warm Climate)
In the historic centre of Mantua, heat recovery can be achieved from ground-floor commercial activities and restaurants. Using a simple air extraction or ventilation system, heat can be redirected into cellars or basements instead of outside.

6.3.9. Air Sourced Geothermal Recovery (2.5)

This concept uses air as a heat source while simultaneously exploiting the more stable temperatures of the underground. It achieves this by extracting heat from underground air sources, such as underground parking spaces or subway tunnels. These spaces maintain stable ground temperatures, largely unaffected by seasonal variations, creating conditions similar to geothermal sources while avoiding the high drilling costs that typical geothermal systems require. This energy recovery solution can be used for heating and cooling and can be applied to heritage buildings in urban neighbourhoods.

Modular panels, designed as structured tubes akin to wall heating or solar thermal collector systems, can be strategically installed along the walls of underground facilities. These panels efficiently extract heat from the surrounding ground and air by circulating a cold heat-carrying fluid through the tubes. For instance, in underground parking structures, these panels can harness residual heat emitted by vehicles, while in metro tunnels, they can tap into the heat generated by passing trains and their braking systems. This innovative dual approach significantly boosts energy recovery potential, promoting a more sustainable urban environment and reducing overall energy consumption.

Though still in development, this technology offers significant potential for scalability. To ensure consistent thermal comfort, additional natural sources, such as standard geothermal energy, can be incorporated into the system. The hybrid nature of this air-sourced geothermal recovery system allows for effective low-temperature heating and cooling (4th and 5th-generation district or neighbourhood networks), making it suitable for various building types within urban neighbourhoods.

Specific Considerations for Norway (Cold Climate)
The concept does not currently occur in Norway.

Specific Considerations for Estonia (Cold Climate)
Estonian city centres also offer diverse functions beyond residential use, making them suitable candidates for this energy recovery solution. Large underground spaces, such as parking lots or tunnels, are available and can be utilised as thermal reservoirs.

Specific Considerations for Belgium (Mild Climate)
In Belgian city centres, where a diverse range of functions beyond residential use exist, the concept is ideal for innovative energy recovery solutions.

Specific Considerations for Italy (Warm Climate)
In Mantua city centre, underground parking lots can be utilised as thermal reservoirs for air-sourced geothermal recovery. However, urban areas in Mantua may face space constraints for geothermal installations, and obtaining regulatory approval for combined systems might be complex.

6.3.10. High Temperature Large-Scale Source Recovery (3.1)

This concept involves a conventional district heating network of the 3rd or 4th generation, depending on the temperature level, with a central heat source from residual industrial heat or a waste incinerator.

As technology evolves, various configurations and integration methods, such as coupling with renewable energy systems, can be explored to create a more holistic energy strategy.

Specific Considerations for Norway (Cold Climate)
In Norway, the concept is already widely applied for city-level district heating systems. This makes it feasible to extend the approach to heritage buildings, provided they are located within urban areas with existing industrial activities and waste management facilities.

Specific Considerations for Estonia (Cold Climate)
Like Norway, Estonia has widely applied city-level district heating systems using high-temperature residual heat recovery.

Specific Considerations for Belgium (Mild Climate)
In Belgium, this concept is already applied for non-heritage buildings, particularly in suburban areas that are closer to industrial plants and waste-to-energy facilities. Heritage buildings, which are often situated farther from these sources, may require additional infrastructure to connect them to these heating networks. Evaluations and modifications to existing systems will be necessary to adapt the concept for heritage buildings.

Specific Considerations for Italy (Warm Climate)
For Italy, specifically Mantua, the implementation of this concept requires an evaluation of the industrial base to identify potential waste heat sources.

6.4. Conclusion

The first five concepts embody typical heat pump systems that utilise conventional natural sources (air, ground, river) or combinations of them. The next five concepts present hybrid systems utilising both residual and natural sources. Large continuous residual sources (wastewater, data centre, and commercial heat recovery) and three somewhat more innovative sources make up the residuals in the hybrid concepts. The former are accompanied by a geothermal or aquathermal natural source, while the naturals accompanying the latter will be defined in the simulations in T4.5. Finally, high-temperature large-scale heat recovery (industrial processes or waste incineration) concludes the list to allow for comparisons with high-temperature district heating networks.

7. Conclusion

This report identifies case study buildings and neighbourhood baselines for energy supply systems. In Estonia, Belgium and Italy, gas is the most commonly used source for heating, while electricity is also a typical alternative for domestic hot water heating. In Norway, electricity is the typical source for heating spaces and domestic hot water. Additionally, in Norway, using wood stoves or fireplaces is a common supplementary heat source during winter when electricity prices are high.

All case study cities have district heating networks and operators, though not necessarily right next to the case study neighbourhoods. In Tallinn and Mantua, connecting to district heating may be more interesting because the district heating network is available in the neighbourhood. In Ghent, there is no plan for the energy company to connect residential buildings to the district heating network. In Trondheim, the district heating network is not directly next to the case study neighbourhood, and buildings typically are not equipped with radiant heating systems, so connecting these buildings to district heating would not be very feasible.

This report also introduces several alternative renewable and residual energy supply systems that can be considered for implementation in case study buildings and neighbourhoods. Constraints and opportunities are considered. Heritage constraints are important, and this report provides general guidelines for case study buildings and neighbourhoods, as well as more detailed considerations that can be found in Annex B: Constraints and Opportunities (Excel file). This report provides information that can be used as a logbook for evaluating the implementation of different energy supply systems in case study buildings and neighbourhoods in the project's later stages.

Finally, this report introduces proposals for longlists and shortlists of energy supply systems in each climate zone and case study country. Although the shortlists are created by professionals, no energy calculations or detailed simulations have been conducted at this stage. The shortlists introduced in this report need further investigation to determine their true potential and feasibility. While some of the proposed shortlisted concepts might not end up being feasible, it was considered important at this stage not to exclude any concept that might later prove to be viable.

The next step is to take these shortlisted energy supply concepts, combine them with shortlisted energy distribution and emission concepts from other deliverables, and study the detailed feasibility of each combination. Heritage constraints can also be evaluated in more detail in the next phase. Results will then be compared using the KPIs identified in other deliverables, and finally, the results can be compared to the overall goals of the HeriTACE project.

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Annex

Annex A: System Description

Download link: https://doi.org/10.5281/zenodo.15752439

Annex B: Constraints and Opportunities (Excel file)

Download link: https://doi.org/10.5281/zenodo.15752492

Annex C: Climate Specific Building Level Intermediate Lists

As explained in Constraints and Opportunities, the general longlist of components for heating, DHW, cooling and storage on building level was reduced to an intermediate list per climate zone based on a scoring system. The items in these intermediate lists are then used as ingredients to construct the building level shortlists for each climate zone that contain the production systems that will be simulated and further assessed.

Intermediate list cold climate

Cold Climate Energy Systems Intermediate List – Building Level	
Production units	Air-to-air Heat Pump
	Air-to-water Heat Pump
	Geothermal Heat Pump
	District heating Heat Pump
	Renewable Biomass Boiler (solid)
	Renewable Biomass Boiler (liquid)
	Renewable Biomass Boiler (gaseous)
Solar systems	STC-panels
	PVT-panels
	PV-panels
	BIPV (Building integrated PV)
Storage	Water Buffer Tank

Intermediate list mild climate

Mild Climate Energy Systems Intermediate List – Building Level	
Production units	Air-to-air Heat Pump
	Air-to-water Heat Pump
	Geothermal Heat Pump
	District heating Heat Pump
Solar systems	STC-panels
	PVT-panels
	PV-panels
	BIPV (Building integrated PV)
Storage	Water Buffer Tank

Intermediate list warm climate

Warm Climate Energy Systems Intermediate List – Building Level	
Production units	Air-to-air Heat Pump
	Air-to-water Heat Pump
	Geothermal Heat Pump
	Open Water Heat Pump (Aquathermia)
	District heating Heat Pump
Solar systems	STC-panels
	PVT-panels
	PV-panels
	BIPV (Building integrated PV)
Storage	Water Buffer Tank