HeriTACE

Feasibility of heat recovery from unharvested local sources in heritage environments

Deliverable D4.3

Version N° 1.0

DOI: 10.5281/zenodo.17940469

Authors: De Vriendt Nicolas (Sweco-BE), Meessens Arno (Sweco-BE)

Funded by
the European Union

Disclaimer

Project Information

Grant Agreement	n°101138672
Project Title	Future-proofing Heritage Townhouses by Optimising Comfort and Energy in Time and Space
Project Acronym	HeriTACE
Project Coordinator	Arnold Janssens, Ghent University
Project Duration	1 January 2024 - 31 December 2027 (48 months)

Deliverable Information

Related Work Package	WP4: Clean energy supply concepts for historical buildings and neighbourhoods (lead: KU Leuven)
Related Task(s)	T 4.3.2
Lead Organisation	SWECO-BE
Contributing Partner(s)	KU Leuven, Universiteit Gent
Due Date	Month 24
Submission Date	18/12/2025
Dissemination level	PU-Public

History

Date	Version	Submitted by	Reviewed by	Comments
08/12/2025	1	De Vriendt Nicolas (Sweco-BE)	Anna Dell'Isola (KU Leuven), Karl Walther (KU Leuven)	Submitted

Table of Contents

List of Figures

List of Tables

List of Equations

Executive Summary

This report presents a comprehensive feasibility assessment of heat recovery from unharvested local sources within heritage environments, focusing on the unique challenges and opportunities present in historic urban neighbourhoods. Conducted under the HeriTACE project as part of the development of clean energy supply concepts for historical buildings and neighbourhoods (WP4), this study seeks to identify, evaluate, and quantify innovative energy supply concepts capable of advancing low-carbon heating while respecting the constraints present in historic neighbourhoods.

Some innovative sources have already demonstrated their benefits in cities where district heating networks are available. This study investigates the feasibility of these sources for smaller collective heating systems in neighbourhoods, consisting of building blocks and small clusters of buildings.

The study employs a two-stage methodology. First, a wide-ranging longlist of innovative residual and renewable energy sources—including unconventional waste heat streams and renewable harvesting technologies—was compiled and qualitatively assessed for proximity (to historical urban neighbourhoods), energy potential, technical feasibility, and heritage-specific restrictions. From this, a shortlist of the most promising concepts was selected for further quantitative analysis, employing hourly profiles, field measurements, and performance modelling.

Among the innovative sources considered, the following residual heat sources were found most promising for heritage settings and subjected to in-depth assessment:

- Continuous waste heat from food chains (supermarkets, grocery stores)
- Micro and small datacentres
- Underground transport facilities such as car parking and metro's tunnels (via ventilation and/or extraction and hydronic wall panels)
- Solar thermal collectors integrated in urban surfaces such as cycling lanes
- Other smaller/intermittent sources including heat from attics of patrimonial buildings, densely populated venues, and vibration (piezoelectric) floors were also evaluated, though with more limited applicability.

Sources such as large datacentres, municipal waste-incineration plants, gravitational battery storage, and rainwater buffering were excluded from detailed analysis due to their distance from historical city centres, limited scalability, or low energy density.

Continuous waste heat sources (food chains, datacentres, underground parking) exhibit high absolute energy potential and, in many cases, a good temporal match with heating demand—especially when their output is used to serve multiple households or neighbourhoods, as shown in Table 1Table 1. When integrated into air-source heat pumps systems, these sources deliver substantial improvements in seasonal Coefficient of Performance (COP), reducing electricity consumption for heating by up to 48% at neighbourhood scale (Table 2).

The most effective sources (food chains, datacentres) can yield significant annual electricity and operational cost savings, making them highly attractive for building or neighbourhood integration. Smaller/intermittent sources (such as attics, fitness venues, piezo tiles) provide only marginal direct savings unless deployed at significant scale. Smaller, intermittent sources only make sense in aggregated or demonstration contexts, given their limited standalone impact.

	Attics - church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Profile match	3,6%	1,2%	0,2%	52,2%	34,6%	39,9%	4,4%	17,3%
Absolute match	11,5%	3,2%	0,3%	88,6%	55,5%	66,8%	5,7%	33,3%
Source match	31,4%	38,5%	65,9%	58,9%	62,4%	59,8%	78,0%	52,0%
COP enhancement	1,12%	20,44%	26,97%	146,69%	160,95%	60,40%	15,55%	108,24%
COP + backup LWP	-1,45%	2,13%	1,25%	103,97%	92,36%	34,85%	0,31%	44,24%

Table 1: The summarised thermal results for the innovative sources at neighbourhood scale

	Attics - church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Annual electrical consumption	288.529	288.167	288.720	148.710	176.255	225.088	285.043	261.299
EC reduction	-0,11%	-0,23%	-0,04%	-48,52%	-38,98%	-22,07%	-1,32%	-9,54%
Electricity cost	€ 129.838	€ 129.675	€ 129.924	€ 66.920	€ 79.315	€ 101.290	€ 128.270	€ 117.584
Cost savings	-€ 141	-€ 304	-€ 55	-€ 63.060	-€ 50.665	-€ 28.689	-€ 1.710	-€ 12.395

Table 2: The summarised economical results for all innovative sources for at neighbourhood scale

This study demonstrates that utilizing innovative sources as thermal energy providers can be generally feasible in urban heritage neighbourhoods. However, the actual implementation and economic viability are highly case-specific, contingent upon factors such as the proximity and availability of these sources, as well as the distance to the targeted neighbourhoods. Further research is needed on what the impact of the case-specific conditions would be and how the investment cost would compare to traditional systems. Within the HeriTACE project (WP4, D4.7), for a relevant selection of unharvested heat sources, the performance will be further investigated by means of energy simulations at small-scale neighbourhood level.

Abbreviations and acronyms

Acronym	Description
ach	Air change per hour
ASHP	Air source heat pump
GSHP	Ground source heat pump
CHP	Combined heat and power
CINEA	European Climate, Infrastructure and Environment Executive Agency
COP	Coefficient of Performance
CRAC	Computer room air-conditioning units
CRAH's	Computer room air-handling units
DC	Datacentres
EER	Energy efficiency ratio
EfW	Energy-from-Waste
EU	European Union
GEP	GEP rainwater buffering system
HR	Heat recovery
HVAC	Heating, Ventilation, and Air Conditioning
IES VE	IES Virtual Environment (software for building performance simulation
IoT	Internet of Things
IRR	Internal Rate of Return
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Kilowatt peak
m^3	Cubic meters
MW	Megawatt
MWe	Megawatt electrical
MWh	Megawatt-hour
MWth	Megawatt thermal
PE	Piezoelectric
PE/PP	Polyethylene/polypropylene
PV	Photovoltaic
PVT	Photovoltaic Thermal
R^2ES	Residual and renewable energy sources
ROI	Return on Investment
SCOP	Seasonal Coefficient of Performance

Terminology

Term	Description
District	Major urban zone that could use a district heating network feeding multiple neighbourhoods
Neighbourhood	Smaller, more localized area within a district, consisting of a building cluster, potentially utilizing smaller-scale shared energy systems.

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 use (Eurostat, 2025). Historic cities in Europe present additional complexity. 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.

In D4.1 of this research project, a long- and shortlist of scenarios for hybrid residual and renewable energy sources (R^2ES) were created. These scenarios are based on current best practices. However, since the HeriTACE project aims to find solutions across time and space, more innovative sources are also being explored. Although these innovative sources have not always proven their efficiency in today's urban contexts, they are promising since no fossil fuels are needed. The focus is on urban historical neighbourhoods, emphasizing local, unharvested sources within heritage environments.

This report explores the potential for recovering heat from unharvested local sources within heritage urban environments. Recognizing the unique challenges of integrating sustainable energy solutions in historic neighbourhoods, the study systematically evaluates a wide range of innovative residual and renewable heat sources such as waste heat from food chains, data centres, underground parking, and urban infrastructure—to identify feasible options that respect conservation constraints. Through detailed simulations, field measurements, and economic analyses, it highlights promising avenues for enhancing energy efficiency and supporting low-carbon heating systems in heritage areas, paving the way for future-proof, sustainable urban living while safeguarding cultural values.

2. Longlist of innovative sources

During the creation of the longlist and shortlist of traditional R²ES-based energy supply concepts, a longlist of innovative sources (Table 3) was developed. This list includes energy sources less frequently used compared to traditional ones, such as air- or water-sourced heat pumps, or aquathermal and geothermal energy.

For each concept in the longlist, a qualitative analysis and estimate of the potential is provided, based on literature studies, reference projects, basic calculations and/or measurements. The potential of an energy source in a heritage environment is not only influenced by the amount of energy, but also by local restrictions. To determine which energy sources are worth researching, first, the proximity of the energy source in heritage contexts is assessed. Since the cost to exploit a source depends on its distance to households, sources that are rarely available in heritage contexts are not pursued further.

Besides proximity, the scale of the energy sources is also a key factor. Implementation of concepts will be easier when multiple buildings can be supplied with energy from the same source.

Based on these descriptions, only the sources with the greatest potential are withhold and studied quantitatively. The results from that analysis will be matched with a general energy demand profile of a heritage building and neighbourhood to demonstrate its potential in this specific context. The results will then indicate what sources prove interesting and which don't match with a heritage context.

Heat sources
Heat recovery from an attic of a large patrimonial
Heat recovery from densely populated spaces
Heat recovery from food chains
Heat recovery from large datacentres
Heat recovery from micro & small datacentres
Heat recovery from ventilation in underground structures
Heat recovery panels in underground structures
Heat recovery of municipal waste burn
Heat recovery from electrical infrastructures
Solar thermal energy from squares, cycle lanes and open spaces
Renewable electricity generators
PV-energy from squares, cycle lanes and open spaces
Vibration energy harvesting
Thermal storage systems
Rainwater heat buffering
Electrical storage systems
Gravitational battery storage

Table 3: Longlist of innovative residual sources

Each concept is explained through following categories:

1. **Technical description**
   The category explains the fundamental working principles, components, and methods involved in each concept
2. **Potential energy production and power**
   This section reviews the capacity of the sources to generate usable heat or electricity.

3. **Proximity in heritage context**
   This category assesses how close specific heat recovery sources are to heritage buildings or neighbourhoods, which influences feasibility. The proximity is largely based on the Ghent case study.
4. **Costs**
   The costs category details the financial implications associated with implementing each innovative heat recovery solution.

2.1. Heat recovery from an attic of a large patrimonial

2.1.1. Technical description

Attics of large patrimonies often become hot due to dark roofs and limited insulation. This means that the air temperature in the attic becomes higher during certain periods than the outdoor air temperature. If the heat in these attics is used as a source for a heat pump, higher efficiencies will be achieved compared to the use of the outdoor air as the heat source.

However, the time of year where the highest temperatures and heat can be measured and extracted, does not overlap with the typical energy demand of a household. Using the heat for domestic hot water could be a solution but a combination with a storage system would be more feasible, like borehole thermal energy storage (BTES) or a tank for seasonal storage. Two options for such systems can be seen on Figure 1 and Figure 2, showing attic extraction combined with BTES and a heatpump and attic extraction combined with seasonal tank storage and two heatpumps respectively. The method for heat extraction out of the attic can use fan coil units or ASHPs.

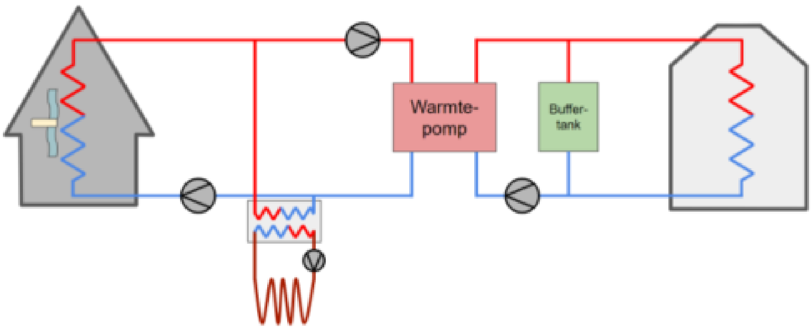

Figure 1: Scheme for heat extraction out of an attic, combined with BTES and a heat pump (Lepinoy, 2023-2024)

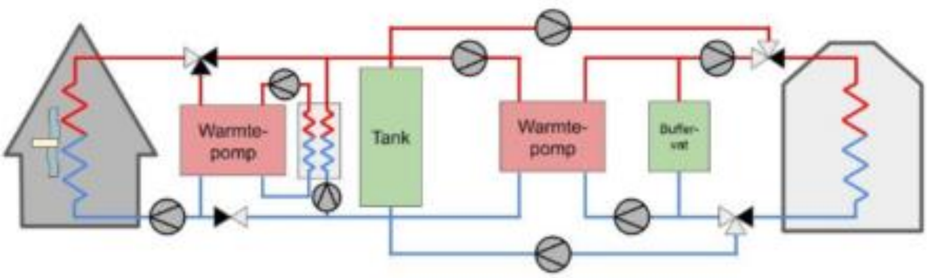

Figure 2: Scheme for heat extraction out of an attic, combined with seasonal tank storage and multiple heat pumps (Lepinoy, 2023-2024)

2.1.2. Potential energy production and power

Simulations, based on a church in Brugge – Belgium, show that the attic of this church can deliver 287 kWh/m²attic/year of heat. However, in large attics the volume is more important than the area. The amount of heat per cubic meter is 110 kWh/m³attic/year (Lepinoy, 2023-2024).

2.1.3. Proximity in heritage context

City centres typically contain a lot of churches. The feasibility of using the attic as a source will improve the closer the households are to the church to limit transportation losses. Attics of different buildings, or other large open spaces that aren't climatised, can be used as well of course, as for example university- or city halls, which are also present in historical centres.

2.1.4. Costs

The cost for heat extraction out of an attic is higher compared to a standard air source heat pump using the outdoor air. The higher costs are due to the additional heat pump (a backup ASHP will still be needed), the careful installation in a historic attic (the stability might not allow for the extra weight) and the required storage facilities for the season mismatch.

2.2. Heat recovery from densely populated spaces

2.2.1. Technical description

In rooms that are often densely populated, the room temperature can rise due to the metabolic activity of the people in the room. Examples of such populated spaces are sports halls, shopping malls, offices, stations, …

The heat can be recovered using a heat exchanger on the extracted air via the ventilation system or on the cooling system. The technology itself is the same as heat recuperation of ventilation systems in houses or offices (apart from the heat now being supplied to a hydronic system), but instead of dumping the excess heat outside, it could be recovered to use in neighbouring buildings. This is not frequently used up until now, which makes the heat source innovative to explore.

2.2.2. Potential energy production and power

The production strongly depends on the volume of the building and the amount of people in the building. Since the amount of heat recovery that could be used is so case-specific not much data is available in literature. Therefore, simulations will be done to gather information.

2.2.3. Proximity in heritage context

Densely populated spaces are sporadically available in city centres. The higher heat outputs will be generated from larger rooms in larger buildings. Typically, the larger buildings are less commonly available in city centres which means that only a limited number of houses would be aided.

2.2.4. Costs

The costs for recovering the heat from densely populated spaces will not be much higher than traditional heat pump systems as the concept itself is widely known (it isn't much applied). Transporting the heat to the required location, potential storage- and backup systems however lead to additional costs.

2.3. Heat recovery from food chains

2.3.1. Technical description

Food stores need large refrigeration systems for storing the food supply. The high cooling demand, which is responsible for approximately half of the electricity consumption (Niklas Söderholm, 2025) of a supermarket, results in a large amount of excess heat. Using this excess heat to heat the store itself, is the most efficient way of reusing this heat due the small distance between source and supply.

When the excess heat is larger than the heating demand of the store, the heat that is still available could be used for surrounding households or buildings. This can be done by connecting the heat recovery system to heat pumps that distribute the heat to assets directly next or above the food store. Alternatively, the heat exchangers and/or heat pumps could be connected to a district heating network (if available) or to small thermal heating networks. The principle of heat recovery from food chains can be seen on Figure 3.

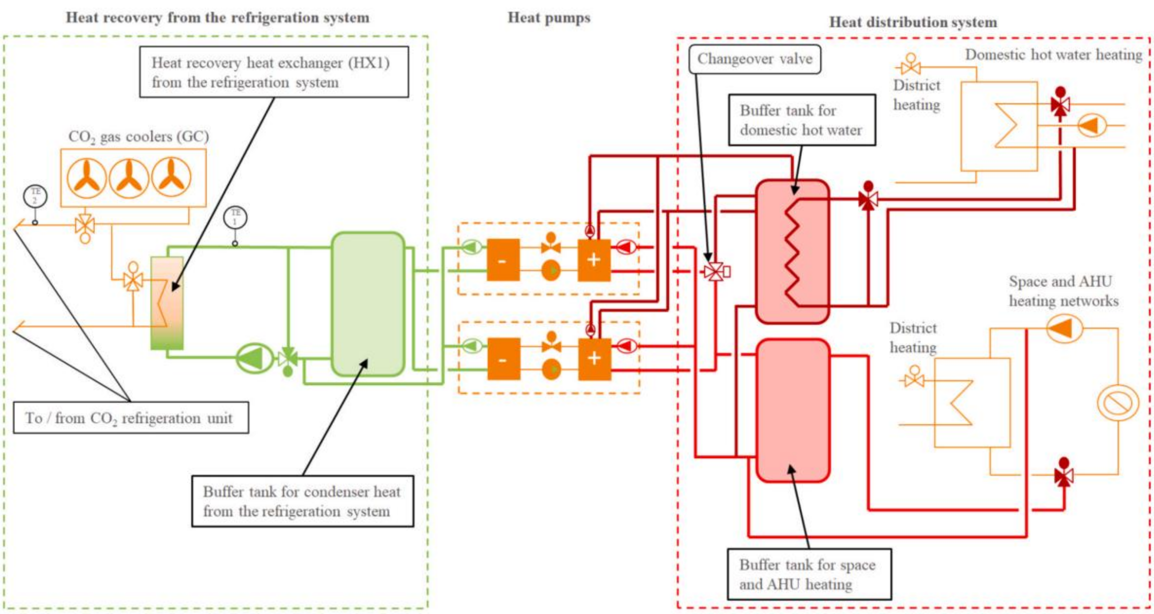

Figure 3: Technical principle of heat recovery from food chains (Niklas Söderholm, 2025)

2.3.2. Potential energy production and power

There are already some examples of heat recovery systems from food stores.

- In Høruphav (Denmark) 20 supermarkets send their surplus heat to the district heating network supplying 16 standard private homes of 130m² (Danfoss, 2015).
- The cooling unit of Coop Rådhuset in Stockholm (Sweden) delivers up to 50 kW cooling power and 20 kW freezing power for the store. On average, the plant supplies around 30 kW to the district heating network (Fjärrvärme, 2015). The shop's cooling system is directly linked to the district heating network and via the secondary circuit also to the district cooling network. This allows heat recovery of all condenser energy in two steps. A conceptual scheme can be seen on Figure 4.

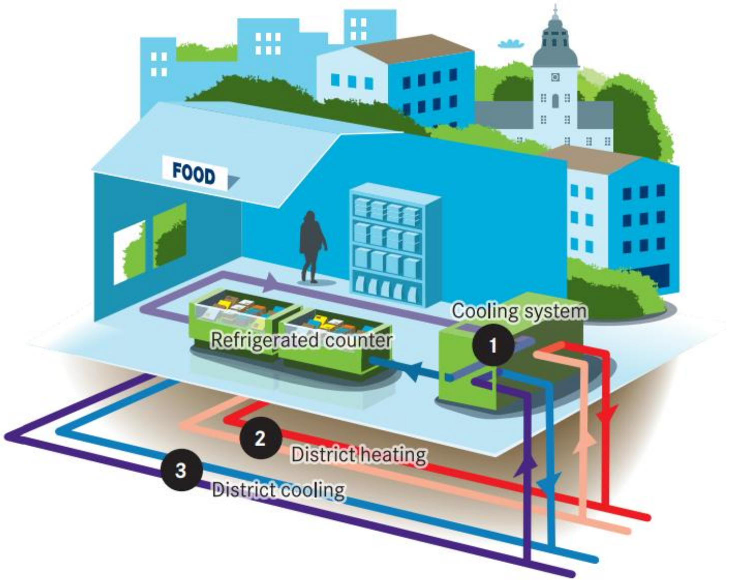

Figure 4: Conceptual principle of heat recovery from food chains (Fjärrvärme, 2015)

The examples above show that most of the existing examples of using the residual heat are cases where the food store is connected to a district heating network. It is less common to transfer the heat directly to neighbours. A KTH research (Julia Almebäck, 2022) of three case studies in Sweden shows however in the techno-economic analysis that it is economically favourable for food stores to cover the internal heating demand with recovered heat from the cooling system, with a great potential to increase the feasibility if a neighbour is willing to pay for the exported heat.

Depending on the size of the supermarket, research indicates that the annual recovery of heat potentially ranges between 1200 MWh and 3500 MWh. In the research field, measurements were done for three supermarkets in Sweden. The amount of excess heat by the cooling was measured as well as the cooling power and EER. From these results the expected excess heat from supermarkets is around 3.500 to 6.500 kWh/kW as shown in Table 4 For these case studies, the mean amount of heat that was recovered for the store was around 30%, which means that 70% of the excess heat could be used for surrounding buildings. The data in the table is visualised in Figure 5.

	case 1: City Gross Ytterby	case 2: City Gross Eskilstuna	case 3: Hemköp Lundby Park
Total excess heat (MWh/y)	1200	790	61
Maximal cooling power (kW)	237	120	17
Total excess heat per maximum cooling power (kWh/kW)	5060	6583	3690

Table 4: Energy and power from literature case study supermarkets

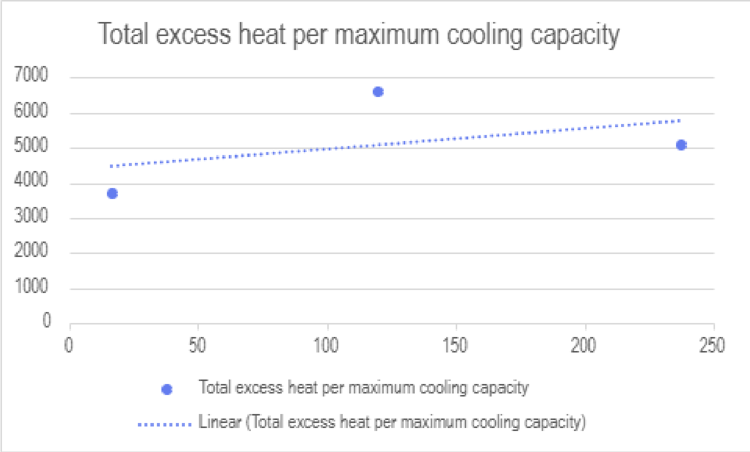

Figure 5: Energy per unit power of the literature case study supermarkets

2.3.3. Proximity in heritage context

Food stores are available in every city, so in theory it is possible to use this heat in every historical neighbourhood. However, the feasibility is the highest when a district heating network is already available as there is a higher demand for the excess heat. The map below shows the district heating facilities in Europe. The residual heat is especially interesting in Denmark, Switzerland, Austria and Czech Republic since district heating networks are commonly available in these countries, as can be seen on Figure 6.

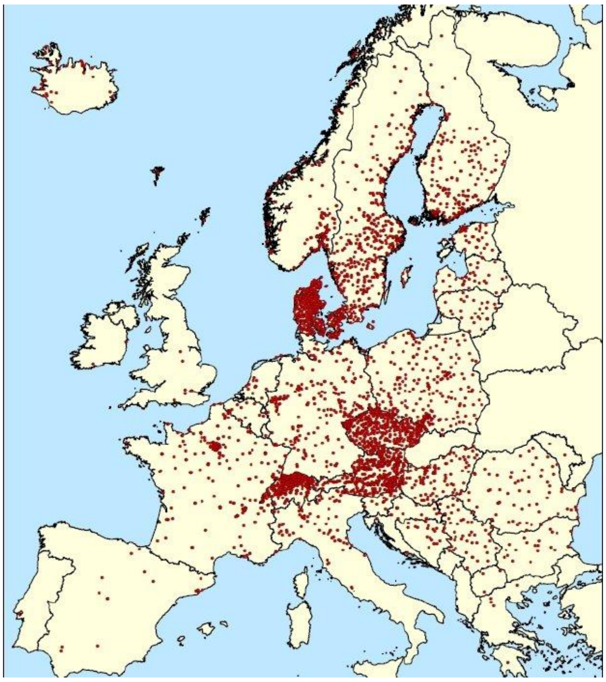

Figure 6: Geographical availability of district heating networks in Europe (Elina Mäki, 2015)

2.3.4. Costs

The largest cost incurred by setting up of a district heating network is the digging for the district heating pipes and the purchase of a pump and heat exchanger. The cost differs per project depending on the distance to the existing district heating network (Danfoss, 2015).

For the project of COOP Rådhuset in Sweden the cost was around 37.000 euro to make the existing cooling system ready to connect with the district heating. This includes the cost of replacing the heat exchanger and pump, rebuilding, control equipment, electrical work and valve installation. An additional 9.100 euro was needed to connect the store to the district heating network.

2.4. Heat recovery from datacentres

2.4.1. Technical description

Information technologies (e.g., artificial intelligence, 5G and cloud computing) have undergone an explosive development in recent years. This evolution emphasized the importance, high-demand and high performance of data centres (DCs). Datacentres require cooling year-round, generating substantial residual heat. Heat recovery in datacentres uses the same principle as in food chains. The recovered heat is often upgraded through a heat pump facility before transport to the buildings.

Depending on the datacentre's size, air or liquid is used as cooling medium. Air-side cooling systems are considered the most used technology in data centres (DCs). They produce high powers at low temperatures and provide reliable waste heat. Their principle can be seen on the schematic Figure 7. However, waste heat utilization from DCs has been widely investigated and is considered low grade thermal heat, which poses a barrier for a widespread use. Compared to air-side, liquid-cooling applications are limited. Their waste heat temperatures are however considerably higher and thus have a higher potential for waste heat re-utilization.

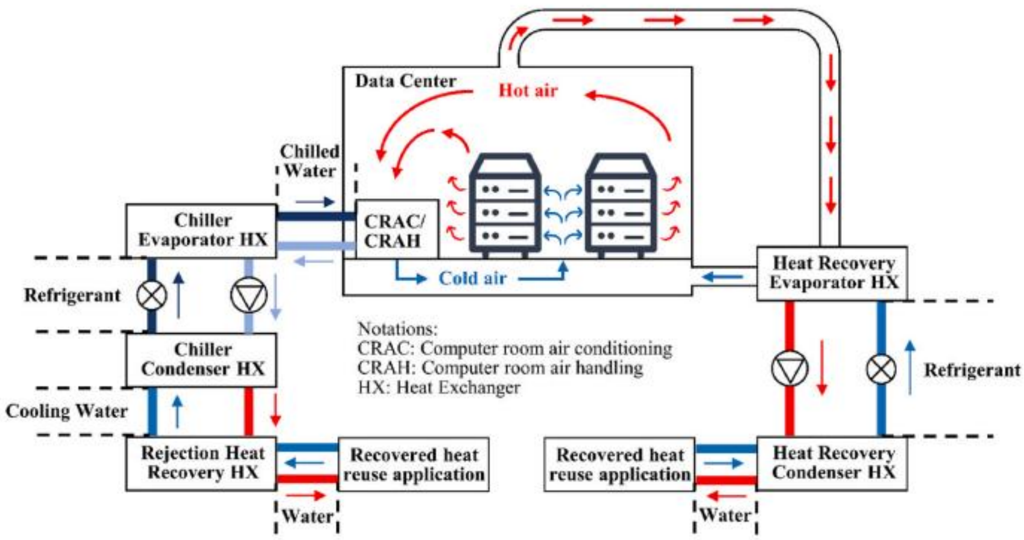

Figure 7: Technical principle of heat recovery from datacentres (Xiaolei Yuan, 2023)

To recover the heat of large datacentres, a district heating network is needed to transport the residual heat to surrounding (residential) buildings. To maximize energy efficiency, buildings connected to the grid must be optimized for low temperature heating. High temperature heating too is possible but causes lower efficiencies of heatpumps.

2.4.2. Potential energy production and power

The potential energy production and power of heat recuperation from the cooling systems strongly depend on the size of the datacentre. Larger datacentres demand more cooling and as such have a larger amount of heat that can be recuperated. 30% - 40% of the energy use of datacentres is dedicated to the cooling demand (Xiaolei Yuan, 2023). Table 5 gives an overview of the different datacentre cooling methods and their characteristics. Figure 8 presents the concept for data centre heat recovery schematically.

CRAC = computer room air-conditioning units

CRAH's = computer room air-handling units

Cooling form	System	Potential heat source	Temperature (°C)
Air-side cooling	CRAC's	Return warm water Return hot air Condenser coolant	15-20 24-47 40-50
Air-to-liquid	CRAH's Heat exchanger	Return warm water Condenser coolant	20-30 40-50
Liquid cooling		Return hot water	50-60

Table 5: Temperature regimes of different datacentre types (Xiaolei Yuan, 2023)

There are a few examples where the residual heat of datacentres is used in residential buildings. Most often this is the case when a district heating network is already available.

- Datacentre of Amazon in Dublin, Ireland: although mainly used to heat public buildings (About Amazon Team, 2020).
- The datacentre of Facebook in Odense, Denmark 100.000 MWh per year of waste heat that could warm up to 7000 houses (Alley, 2020).
- Dataparks in Stockholm like Bahnhof Thule with a heating power of 1600 kW (celsiuscity, 2020).
- Telia Helsinki data centre.
- Branuschweig in Germany, 1750 MWh per year (Rudzka, 2019).

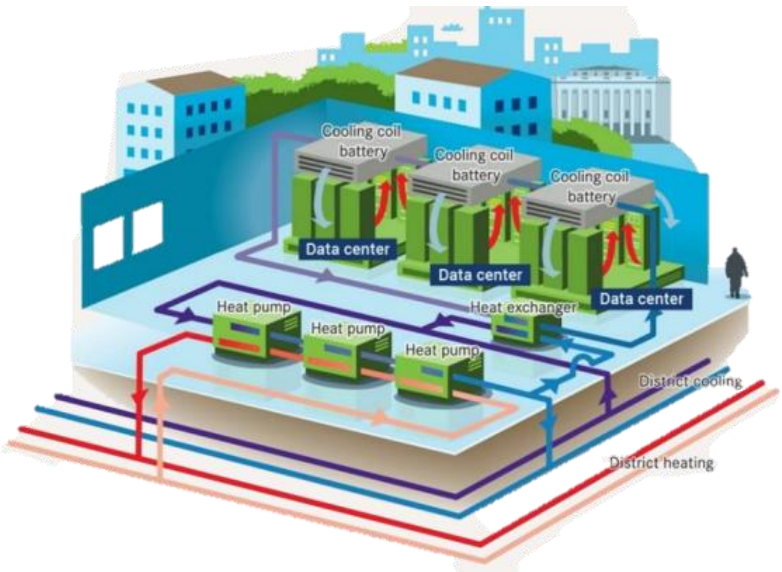

Figure 8: Conceptual principle of heat recovery from datacentres (celsiuscity, 2020)

2.4.3. Proximity in heritage context

Large datacentres won't normally be located close to historical urban city centres. But if a district heating network is available, the heat could also be used for residential buildings in these historical neighbourhoods.

2.4.4. Costs

The costs strongly depend on the size of the datacentre and cooling installation. The largest investment cost is setting up and connecting the heat recovery system to a district heating network, which could cost several million euros. The investment cost is however economically feasible with an IRR above 10% over a period of 30 years (Murphy, 2021). For homeowners, only the connection cost to the district heating network is required.

If the heat of computer room air-conditioning would be recovered, the cost will be mainly determined of the distance to the source. Costs are in both cases specific to the project.

2.5. Heat recovery from ventilation in underground structures

2.5.1. Technical description

Underground air structures, as for example subway tunnels, are characterised by the same principles which make geothermal systems very interesting. Namely, the deeper one goes, the higher the underground temperature rises and lower the impact of seasonal differences becomes. As a bonus, the metros itself produce waste heat: energy from braking and evacuated heat from the people inside the vehicle. It is expected that the air temperatures inside the tunnels therefore exceed the ambient ground temperature. Heat extraction from these tunnels would therefore cause high SCOPs due to stable and relatively high temperatures. The typical downside of these systems, namely the high drilling costs, can be avoided as the subway tunnels are already in place. This makes heat extraction from these underground air structures very promising. Perhaps also worth mentioning that in summer, the ground becomes very warm, which has negative effects on biodiversity; thus, recovering heat from these tunnels also provides an additional positive environmental benefit.

This heat can be recovered using heat exchangers. The heat exchangers are placed at the ground level and the warm air is transported through a ventilation shaft. Different methods can be thought of as can be seen on Figure 9 and Figure 10. There are several options for providing cooling, together with waste heat recovery from the tunnel air, which includes (Gareth Davies, 2017):

- the use of a fan coil heat exchanger in a ventilation shaft
- the use of air handling units (AHUs), which involves the installation of heat exchangers located above underground station platforms, which are supplied with chilled water to provide cooling
- the use of pipes running along the inside of the tunnel walls, through which cold water is pumped to supply cooling

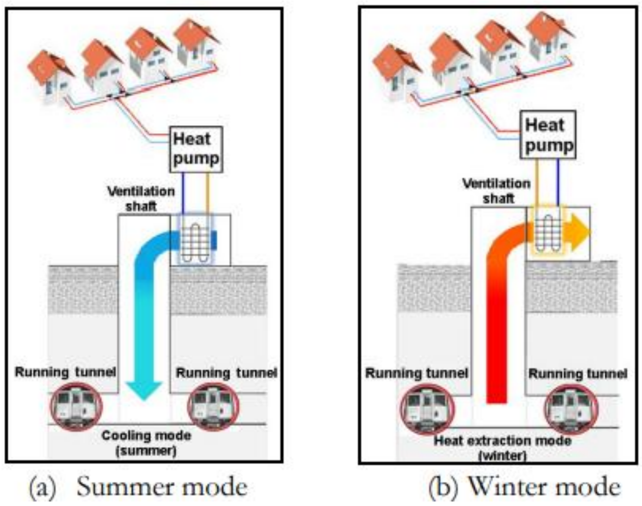

Figure 9: Conceptual drawing representing heat recovery form underground air structures (Gareth Davies, 2017)

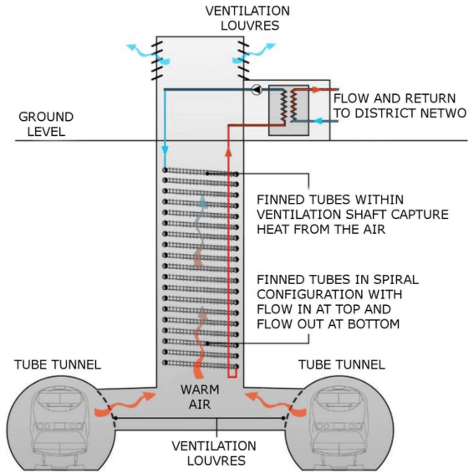

Figure 10: Conceptual drawing representing heat recovery form subways (ReUseHeat Project, 2017)

2.5.2. Potential energy production and power

The EU-funded CELSIUS project in London captures waste heat from London Underground tunnels. Currently, most of the heat is absorbed in the tunnel walls and approximately 10 % of the heat is removed by mechanical ventilation.

Finned tubes within the ventilation shaft capture heat from the air. The ventilation shaft expels exhaust air at a rate of 30 m³/s with a temperature of 22°C in winter and 28°C in summer. A feasibility study found that the heating power of the ventilation shaft would be approximately 400 kW. By increasing exhaust air flow rate to 70 m³/s the heating power would be increased to 1000 kW. Hereby, low-grade waste heat is recovered from the ventilation shafts through an air-to-water heat pump (ReUseHeat Project, 2017).

2.5.3. Proximity in heritage context

A lot of big cities with historical city centres have subways or underground air structures. In cities with metro stations, the heat within the underground air structures can be recovered. Figure 11 shows the geographical availability of subways in Europe.

Figure 11: Geographical availability of subways in Europe

2.5.4. Costs

Compared to traditional heat pump systems, the investment costs will be higher due to the needed heat exchanger and piping trajectory. Installation costs for heat exchangers in ventilation shafts are high due to limited accessibility (CELSIUS, 2017).

2.6. Heat recovery panels in underground structures

2.6.1. Technical description

Heat recovery panels, like those from Enerdrape that can be seen on Figure 12 (Enerdrape, 2025), are thin, hydronic heat-exchange panels installed on walls (and ceilings) of underground car parks. The parking walls and the warm air inside the parking conduct and exchange heat to the panels. Inside each panel runs a closed loop of water or glycol that picks up that low-grade heat. The warmed fluid is piped to a heat pump that upgrades the low-temperature thermal energy to useful heating temperatures (for space heating or domestic hot water).

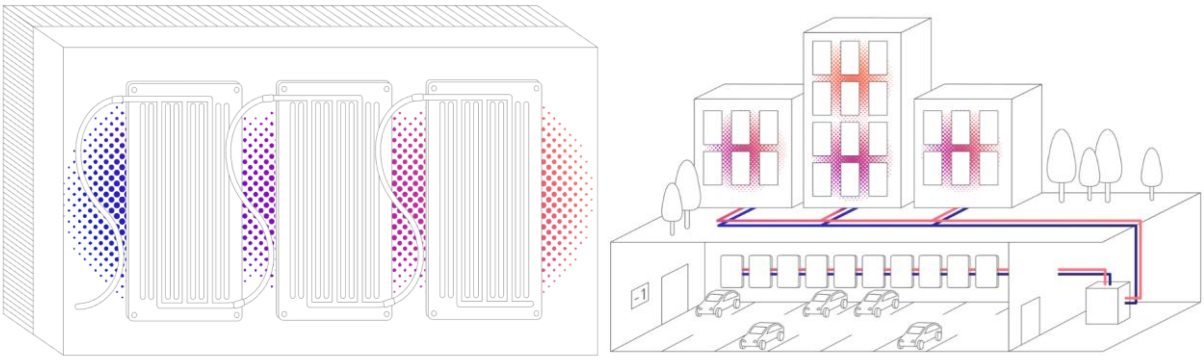

Figure 12: Example drawings of hydronic panels in underground car parks (Enerdrape, 2025)

2.6.2. Potential energy production and power

Available heat power depends on garage size, occupancy and ventilation. Typical recoverable heat fluxes for busy underground car parks lie in the range 5–20 W/m² of floor area (higher when densely occupied or poorly ventilated). For example, a 2,000 m² garage could commonly yield 10–15 kW of continuous thermal power during busy periods – roughly 100–300 MWh of low-grade heat per year depending on usage patterns (Enerdrape, 2025).

2.6.3. Proximity in heritage context

Underground car parks are often found in historical city centres and are very well suited to heat recovery. The short pipe distances reduce distribution losses and civil interventions in protected streets and facades. However, historic areas may impose constraints: restricted access for installation, limits on visible plantroom equipment, strict rules on digging and changes to façades, and noise/ventilation restrictions for new mechanical plant. These constraints make compact systems with minimal external impact (ceiling-mounted panels, small heat pump units installed in discrete plantrooms or basements) particularly attractive.

2.6.4. Costs

Upfront costs include panels and fittings, hydraulic distribution (pipes, pumps, valves), a heat pump sized to the recovered power, controls and any ventilation or filtration upgrades.

2.7. Heat recovery of municipal waste burn

In 2023, 45% of municipal waste was burned in Belgium as can be seen on Figure 13 (STATBEL, 2025). The total amount of municipal waste in Flanders was equal to 4.58 million tons in 2022 (circulair, 2022). A lot of residual heat can be recovered from the municipal waste burn, however, as many communities have the ambition to recycle more and avoid extra waste, the potential for heat recovery will lower in the future.

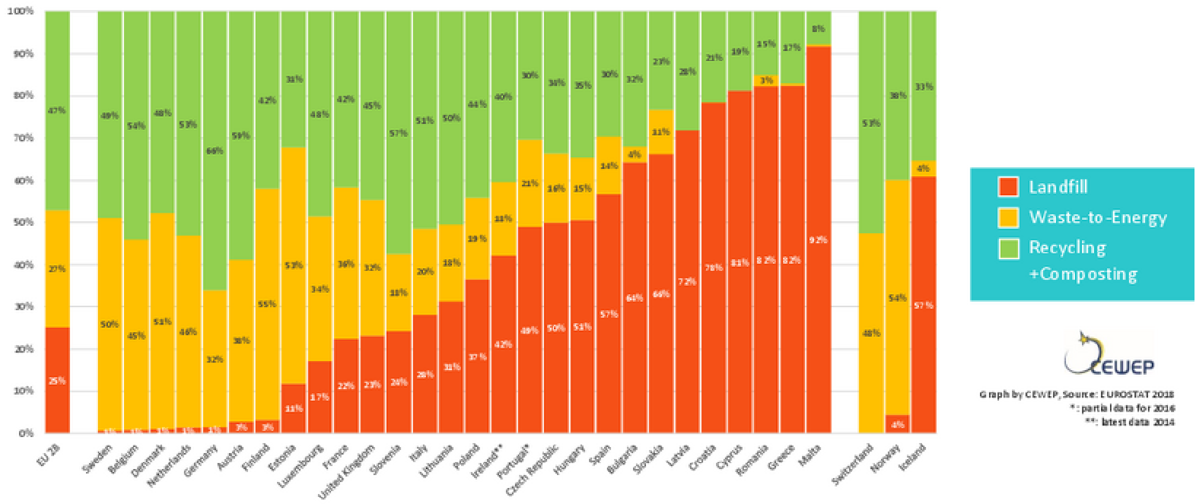

Figure 13: Municipal waste treatment of EU 25 + Switzerland, Norway and Iceland in 2016 (Belgian waste to energy, Wat is waste-to-energy?, 2016)

2.7.1. Technical description

Municipal waste combustion plants (incinerators / energy-from-waste, EfW) convert the chemical energy in municipal solid waste into heat by controlled combustion. The core process produces high-temperature flue gases and steam in a boiler, which is typically used to drive a steam turbine for electricity generation (CHP) and to supply hot water/steam to a district heating network. Modern installations recover additional heat through flue-gas economizers, air-preheaters and heat exchangers, and may use condensation of water vapour in flue gases (condensing economizers) or secondary heat pumps/ORC (organic Rankine cycle) units to extract low-grade heat. A full CHP configuration captures both electricity and useful thermal energy, while heat-only or heat-led operation prioritises supplying hot water/steam to end users (district heating, industrial processes) and often achieves higher overall energy utilisation.

2.7.2. Potential energy production and power

Energy output depends on plant size and waste calorific value (typically 8–12 MJ/kg for mixed municipal waste in Europe (Hussein Janna, 2021)). A medium EfW plant treating 100,000 tonnes/year of waste roughly corresponds to a thermal input of 20–35 MWth. Such a plant is delivering 5–15 MWe of electricity plus 10–30 MWth of recoverable heat in CHP. The available residual heat is thus very continuous and large.

2.7.3. Proximity in heritage context

EfW plants are not sited inside historic city centres due to land, emission control and visual/aesthetic constraints, but many European cities operate compact or underground facilities near urban cores or connect peripheral EfW plants to nearby district heating networks serving historic centres.

2.7.4. Costs

Capital costs vary with scale and pollution control complexity. Modern EfW CHP plants with advanced flue-gas cleaning typically have CAPEX in the range €3,000–6,000 per tonne of annual waste capacity (so a 100,000 t/yr plant ≈ €300–600M, though smaller, modular, or retrofit solutions and economies of scale change this markedly). Additional costs cover district heating network construction (pipes, substations, insulation) – typically several hundred to a few thousand euros per metre for urban installs depending on excavation difficulty and reinstatement in historic streets.

2.8. Heat recovery from electrical infrastructures

2.8.1. Technical description

Electrical distribution stations house power electronic devices that alter the frequency of the electrical current. High-voltage cables enter the cabin, and a transformer converts high voltage to low voltage. This low voltage is distributed via the low-voltage panel through several departing low-voltage cables to reach grid users.

The distribution cabinets heat up due to the equipment, especially the transformer. To prevent excessive temperature rise, cooling methods compensate for the heat and control the transformer's temperature. Various coolants used for transformer cooling include air, synthetic oils, mineral oils, gas, and water (Ltd, 2025).

In Belgium, city-distribution-cabinets are cooled by surrounding air through natural convection. The rooms are ventilated to:

- Keep the average daily temperature below 35°C.
- Ensure the room temperature does not exceed the ambient temperature by more than 10°C.

2.8.2. Potential energy production and power

Depending on the electrical power of the transformer and the resulting generated heat, the ventilation should be designed to comply with the cooling needs in Belgium. The heat that should be evacuated, and thus can be recovered, is calculated as follows:

$$Q_{recoverable} = (P_0 + \beta^2 \times P_k + P_{other}) \times \mu_{HR} \times T$$

with:

$Q_{recoverable}$	the recoverable heat on yearly basis
P_0	No load losses (kW)
β	Average load factor, in this case 60%
P_k	Short circuit losses (kW)
P_{other}	Other heat losses (kW)
μ_{HR}	Efficiency of the heat recovery system, in this case 75%
T	Number of hours in a year

Equation 1: Recoverable heat from distribution cabinets

Power	No-load losses	Short circuit losses	Other heat losses	Yearly recoverable heat (kWh)
630 kVA	540 W	4600 W	450 W	17.384
800 kVA	585 W	6000 W	700 W	22.634
1000 kVA	693 W	7600 W	700 W	-

Table 6: Yearly recoverable heat for different power levels of electrical infrastructure

The heat extracted from these infrastructures can be recovered and used for heating using an air-to-water heat exchanger. Since the exhaust air will be only slightly warmer than the outside temperature, a heat pump will be required to raise the temperature to levels suitable for distribution systems. Table 6 presents the yearly recoverable heat for different power levels of electrical infrastructure.

However, strict safety rules must be followed regarding the electricity grid. For safety reasons, the government or energy distributor may not permit adjustments to the cabinets.

2.8.3. Proximity in heritage context

Many cabinets are available in cities. Transformer stations distribute electricity to the client cabinets. Figure 14 and Figure 15 show the client cabinets (orange) available in the case-study neighbourhoods in Ghent. A transformer station with a withdrawal capacity of 78 kVA (fluvius, 2025) feeds these client cabinets.

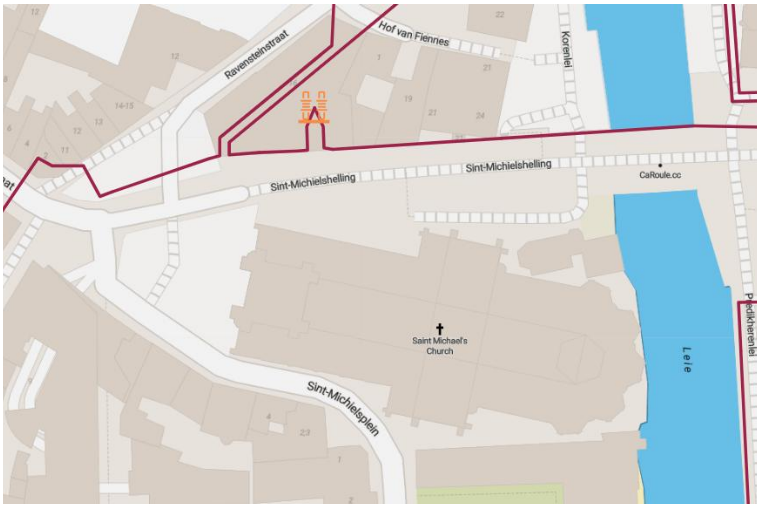

Figure 14: Availability of electrical cabinets near Sint-Michiels plein in Gent (fluvius, 2025)

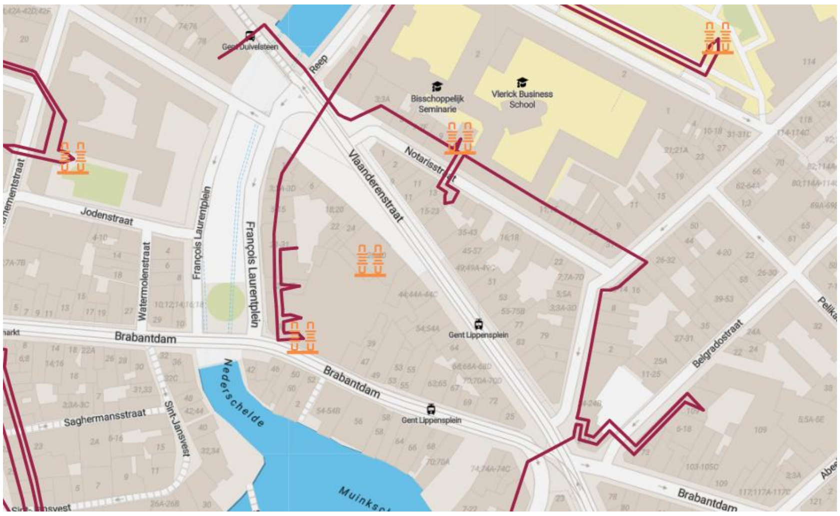

Figure 15: Availability of electrical cabinets near Vlaanderenstraat Gent (fluvius, 2025)

2.8.4. Costs

For smaller distribution cabinets that are cooled by natural ventilation, an air-to-water heat exchanger is required. The cost of this system compared to a conventional heat pump, which is still needed afterward, will increase by a few thousand euros, which is due to the extra heat exchanger. Additionally, a pipeline route must be provided.

2.9. Solar thermal energy from squares, cycle lanes and open spaces

2.9.1. Technical description

Solar-thermal asphalt collectors embed heat-absorbing pipes or fluid channels within or beneath the road or cycleway surface to capture solar irradiation and ambient heat as cen be seen on Figure 16. Typical systems use a network of plastic (PE/PP) or metal tubing placed a few centimetres below the asphalt layer through which a heat transfer fluid (water or glycol) circulates. The warmed fluid is pumped to a heat exchanger, buffer storage or a heat pump that upgrades the low-temperature heat for space heating or domestic hot water. Designs vary from shallow "active" collectors integrated during resurfacing to modular prefabricated panels retrofitted into pavement joints; thermal insulation under the collector limits downward losses while the asphalt itself acts as a collector and thermal capacity. Import to note is that the pavement or cycle lane should not be designed to collect more heat (e.g. by making it black if that was not intended) as this could enhance the heat island effect if no heat would be extracted temporarily in summer.

Figure 16: Asphalt road collector (Cyclifier, 2004)

2.9.2. Potential energy production and power

Energy yield depends on local solar irradiation, collector area, pavement albedo, thermal coupling and collector efficiency. Asphalt collectors are low-grade solar thermal devices with typical annual yields in the range 150–400 kWh/m² of collector area in central-western Europe, but practical recoverable energy for cycling lanes is often at the lower end because of shading and vehicle/pedestrian wear – a conservative estimate for a well-installed lane in Belgium is 100–250 kWh/m²·yr (Cyclifier, 2004).

2.9.3. Proximity in heritage context

Cycle lanes typically run through dense urban fabrics, so heat collected from asphalt cyclists' lanes can be very close to heat demand in historic city centres. The short distribution distances reduce thermal losses and avoid major civil works in sensitive areas. However, installing or retrofitting collectors in historic streets faces challenges: conservation rules may restrict significant changes to pavements and surfaces, archaeological concerns require careful excavation protocols, and aesthetic requirements may limit visible equipment (manholes, housings). Besides, asphalt lanes in city centres could have lower efficiencies due to shadow from the neighbouring buildings.

2.9.4. Costs

Installed costs depend on collector type, excavation difficulty and system peripherals (pumps, heat exchangers, storage, heat pump). For new construction or major resurfacing, integrated asphalt collector add-ons are relatively inexpensive per m² – ballpark installed costs commonly range from €50–200/m² for the collector network and basic hydraulics.

2.10. PV-energy from squares, cycle lanes and open spaces

2.10.1. Technical description

Solar panels are typically installed on roofs or in areas not frequently used by people. However, there are numerous open spaces suitable for PV panels, such as cycling roads or in between train rails. Unlike traditional panels, those placed on roads must have enhanced stability. Solar cells are fitted beneath a tempered glass top layer of approximately 1 cm thick (SolaRoad, Press release: SolaRoad opens the first road in the world that converts sunlight into electricity is ready for use, 2014). The principle is shown on Figure 17. The same holds for panels between train tracks; they should be resistant to many heavy vibrations and debris/dirt that might hit the panels.

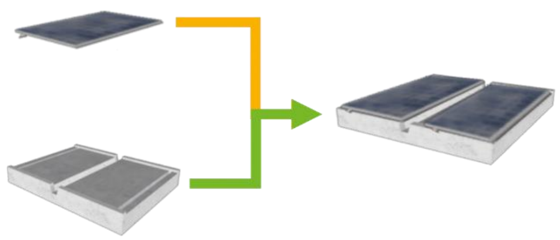

Figure 17: SolaRoad panel principle (SolaRoad, Product development, 2025)

2.10.2. Potential energy production and power

A Dutch company, SolaRoad, produced robust solar panels with a skid-resistant, translucent coating mounted on concrete slabs. The company's goal was to produce 100 kWh/m² (SolaRoad, Press release: SolaRoad opens the first road in the world that converts sunlight into electricity is ready for use, 2014) per year, utilizing solar power from the road for practical applications in street lighting, traffic systems, electric cars, and households. The first tests generated an excess of 3000 kWh, translating to more than 70 kWh/m² per year (Howard, 2015). Testing has also been done on car roads. However, problems arose shortly after testing.

2.10.3. Proximity in heritage context

If the technology can improve stability, it can be easily installed on cycling paths in urban neighbourhoods. Of course, special attention must be put towards the placement in regards to shading due to surrounding buildings. The colour of the solar panels can match the roads as closely as possible to avoid disturbing the view of the neighbourhood.

2.10.4. Costs

The costs are currently high due to development expenses compared to traditional rooftop solar panels. Solar panels integrated into roads are not feasible for commercial production at this time. Further research is required to enhance the stability and lifespan of these solar panels.

2.11. Vibration energy harvesting

2.11.1. Technical description

This technology harnesses ambient mechanical vibrations and converts them into electrical energy, thereby enabling self-powered sensors, IoT, and other low-powered electronics. There are four distinctive approaches:

- Piezoelectric
- Electrostatic
- Electromagnetic
- Triboelectric

Piezoelectric materials possess the ability to generate electrical charge in response to mechanical stress, making them well-suited for harvesting energy from mechanical vibrations (Mohammad Farhan, 2024).

2.11.2. Potential energy production and power

There are already piezoelectric tiles available on the market. The electricity generated from these tiles equals 35 Wp/m² (Energy Floors, 2025). In literature, a similar number can be found in a case study of a dance club in Rotterdam: 5-20 W/person on a tile of 75x75 cm (Rania Rushdy Moussa, 2022). The range relates to the intensity with which the person dances. Another case study presents these panels at the entrance gates of the Tokyo station Yaesu.

2.11.3. Proximity in heritage context

The tiles can be installed on every public floor, preferably with a high passage. So, in theory all large spaces could be used such as squares, train station entrances, pedestrian cross walks etc. Also, a temporal approach seems possible, e.g. markets and festivals.

2.11.4. Costs

Capital costs are high relative to energy delivered. Prototype and commercial piezoelectric floor tiles typically range from several hundred to a few thousand euros per square metre installed (including tiles, power electronics and basic storage. Operating costs are low but maintenance and replacement can be non-trivial if modules are exposed to heavy cyclic loading, moisture or vandalism. Given the low energy yield, monetised energy savings are small; most current business cases rely on non-energy benefits (public engagement, demonstration) or integration with other objectives (tourism, temporary events).

2.12. Rainwater heat buffering

2.12.1. Technical description

Rainwater buffer tanks can be used to store heat. They can be seen as small thermal heating storage systems. In the rainwater tank, a heat exchanger is placed in direct contact with a heat pump in the building. The rainwater tank is in this case the heat source similar to aquathermal and riothermia heating systems. This system can ideally be combined with solar thermal panels or PVT-panels.

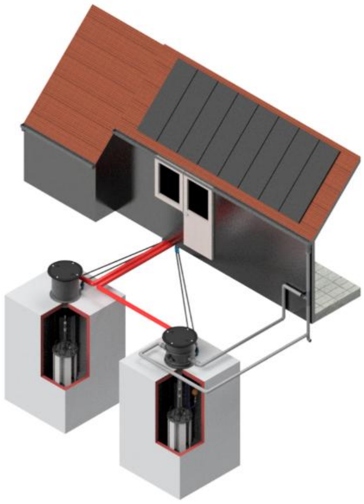

Figure 18: Principle of GEP rainwater buffer tanks (GEP, sd)

2.12.2. Potential energy production and power

GEP states that their system can deliver a continuous heat source for a heat pump of 3,5 kW when a tank of 7000L is used (GEP, sd). The energy density would be 60-80 kWh/m³ (Amaya V. Novo, 2010) for storage systems 5 to 15 metres deep. The principle can be seen on Figure 18.

2.12.3. Proximity in heritage context

Since it is a system that is more suitable for an individual household, it can be rather easily installed for a building with a garden area available. Large-scale water buffer systems are possible but require significant work, which can greatly impact the neighbourhood. This limits their feasibility, especially in heritage neighbourhoods.

2.12.4. Costs

The investments cost for a GEP-system is around 25.000 euro.

2.13. Gravitational battery storage

2.13.1. Technical description

A gravity battery stores potential energy by moving a mass against Earth's gravitational force. During energy surplus periods, like excess wind or solar power, this energy raises a heavy mass, such as water or concrete blocks, to a height. When energy demand is high and supply is insufficient, the mass is lowered. The descending mass converts the stored potential energy into kinetic energy, which a generator then converts into electricity (Chaturvedi, Yadav, Srivastava, & Kumari, 2020).

2.13.2. Potential energy production and power

The energy yield of a gravity battery can be calculated using the formula for gravitational potential energy: $E = m \cdot g \cdot h$, where E is the energy in joules, m is the mass in kilograms, g is Earth’s gravitational acceleration (9,81 m/s²), and h is the height in meters.

For example, if a mass of 100 tonnes is raised to a height of 100 meters, the potential energy is calculated as: E = 100.000 kg · 9,81 m/s² · 100 m = 98.000.000 J, resulting in 98 megajoules or 27 kWh of potential energy, which can be converted into electrical energy depending on the efficiency of the generator.

It's clear that heavy masses or great depts are needed to store energy. That’s why this technology is primarily used in mineshafts, as demonstrated in Finland by the Scottish company Gravitricity (McConnell, 2024) or in Switzerland by EnergyVault (Vault, 2024).

2.13.3. Proximity in heritage context

Mineshafts are often abandoned, which benefits gravitational battery storage. Figure 19 shows numerous mineshafts in Europe, but they are often not located near historical parts of cities. (The green circles represent the calculated amount of waste rock where the largest circles represent more than 500 Mt of waste rock. Diamonds represents smaller mines. The colours represent the type of ore; blue for iron and iron-alloy metals, yellow for precious metals, red for base metals, grey for bauxite, violet for energy metals (U) and green for special metals (Anna Ladenberger, 2018)).

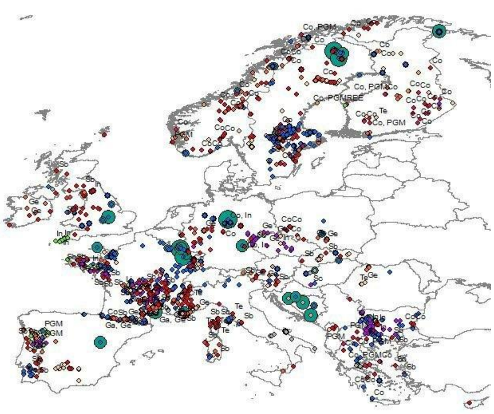

Figure 19: Geographical availability of mines in Europe (Anna Ladenberger, 2018)

2.13.4. Costs

The costs are currently high. The cost of a demonstration project of Gravitricity in Edinburgh costed one million pounds for just 15 meters (Keane, 2021).

2.14. Overview

Table 7 provides a qualitative overview of a sources' availability in historical city centres, the energy potential of each source and if any practical restrictions or technical limitations hinder the source. Costs are left out of the summary as, due to technological developments, they are expected to decrease with time and don't pose a relevant criteria at the moment.

Some innovative sources have already demonstrated their benefits at city level where district heating networks are available. In this overview the feasibility of these sources is given for smaller neighbourhoods, consisting of building blocks and small clusters of buildings.

The following colour code is used:

- Proximity in heritage context
    - Red: Almost never available in heritage districts; high limitations or impracticality.
    - Orange: Sometimes available, but with modest potential or access challenges.
    - Green: Commonly available close to or within heritage areas, offering promising opportunities.
- Potential energy production and power (assuming no storage)
    - Red: Limited or negligible energy potential; not viable for significant heat supply/power.
    - Orange: Moderate potential, possibly useful with aggregation or supplementation.
    - Green: High energy potential, suitable for direct or hybrid energy systems in heritage contexts.
- Restrictions or technical limitations
    - Red: Major restrictions or technical infeasibility; very limited applicability.
    - Orange: Some restrictions exist; technical challenges can be managed with effort.
    - Green: Few or no restrictions, conducive to implementation within heritage environments.

	Proximity in heritage context	Potential energy production and power	Restrictions or technical limitations
Heat sources			
Heat recovery from an attic of a large patrimonial			
Heat recovery from densely populated spaces			
Heat recovery from food chains			
Heat recovery from large datacentres			
Heat recovery from micro & small datacentres			
Heat recovery from ventilation in underground structures			
Heat recovery panels in underground structures			
Heat recovery of municipal waste burn			
Heat recovery from electrical infrastructures			
Solar thermal energy from squares, cycle lanes and open spaces			
Renewable electricity generators			
PV-energy from squares, cycle lanes and open spaces			
Vibration energy harvesting			
Thermal storage systems			
Rainwater heat buffering			
Electrical storage systems			
Gravitational battery storage			

Table 7: Overview of potential of innovative sources

3. Shortlist of innovative sources

Not all sources in the longlist are interesting to use in the context of historical households or neighbourhoods. Furthermore, when investigating feasibility, one may encounter limited returns, technological difficulties, and/or restrictions. Due to these reasons, certain sources lack enough potential for a thorough, quantitative analysis. Table 7 summarised how each source performed qualitatively on the different criteria. This chapter explains why the sources that have scored badly on one of the criteria (indicated in red) will not be studied further.

3.1. Not withhold concepts

3.1.1. Due to proximity in heritage context

Large datacentres are not often found in historic city centres because their scale and site requirements generally place them outside dense urban cores. These facilities produce large amounts of low-grade heat that can be usefully recovered into district heating networks when available, but their size, cooling infrastructure and land needs mean they rarely sit close to the compact heat demand in historic neighbourhoods.

Municipal waste-burn (energy-from-waste) facilities are likewise typically sited outside city centres for hygiene, emissions control and land-use reasons. They generate substantial residual heat that is well suited to feeding large-scale district heating networks, and when connected to such networks can deliver high overall energy utilisation. However, integrating this residual heat into small, local thermal networks at building or neighbourhood scale in historic areas is usually impractical: distribution distances, infrastructure scale and the need for large transfer substations mean EfW heat is a system-level rather than strictly local solution.

Gravitational battery storage—lifting and lowering heavy masses in shafts or towers to store and release energy—depends on large, well-maintained vertical voids (mineshafts, purpose-built towers) and significant civil works. Because suitable shafts are location specific and require robust maintenance and safety regimes, gravitational storage cannot be assumed available in historic city centres and must be assessed on a case-by-case basis.

3.1.2. Due to potential energy production and power

Rainwater heat buffering is excluded from further study because its realistic energy yield and output power are too limited to make a meaningful contribution in the historic-centre context. Published performance figures show the system is sized for single-building support rather than neighbourhood supply. Even when combined with solar thermal or PVT, the absolute stored energy per footprint remains small and highly dependent on local rainfall and seasonal charging opportunities. Large collective buffer volumes could serve an answer to this problem but cause difficulties in relation to placement and location in dense centres.

Scalability is poor: deploying many tanks to match a neighbourhood-scale demand would require large areas (gardens or voids) and significant capital, while installation in constrained, heritage streetscapes is rarely feasible.

For these reasons – low absolute energy density and power output and limited scalability – rainwater heat buffering is not considered a promising candidate for further study in the context of innovative solutions for historic city centres.

3.1.3. Due to restrictions or technical limitations

Electrical infrastructure in urban neighbourhoods often lacks the capacity for active cooling using water, oils, or mechanical ventilation. Consequently, heat recovery from active cooling or mechanical ventilation is not feasible. Typically, only natural ventilation is used. The internal temperature of electrical cabins matches the external temperature, limiting the benefits of heat recovery from the natural exhaust air.

Since issues arose in the test cases, PV energy from squares, cycle lanes and open spaces is not further explored in this research. Its technical feasibility could not be established. While production improvements may make this source viable in the future, the multitude of failed projects and testcases suggest the exclusion of this innovative concept.

3.2. Withhold concepts

The following chapters will investigate the potential of the withhold concepts thoroughly via simulations and in-depth calculations. Table 8 summarizes the withhold concepts.

Heat sources
Heat recovery from an attic of a large patrimonial
Heat recovery from densely populated spaces
Heat recovery from food chains
-
Heat recovery from micro & small datacentres
Heat recovery from ventilation in underground structures
Heat recovery panels in underground structures
-
-
Solar thermal energy from squares, cycle lanes and open spaces
Renewable electricity generators
-
Vibration energy harvesting
Thermal storage systems
-
Electrical storage systems
-

Table 8: Withhold innovative concepts

4. Methodology in depth analyses

The withhold concepts are examined using simulations or calculations based on hourly profiles. In some cases, temperature measurements were conducted to verify the simulations or serve as initial data for the calculations.

4.1.1. Temperature measurements

In relation to innovative sources, two temperature measurement campaigns were carried out in the case-study neighbourhood of Ghent, Belgium.

Temperature measurements were taken in the Sint-Michiels church. Two sensors were placed in the attic of the church at two different heights, and one meter in the choir of the church as a reference for the indoor temperature in the church.

The second measurement campaign occurred in the underground parking lot of the Sint-Michiels neighbourhood, which has three floors. Each floor is measured and an additional measurement is conducted near the entrance on the first underground floor to check the influence of the open entrance.

All measurements were performed using *HOBO U12 Temp/RH* data loggers (Onset Computer Corporation).

Corresponding climate data from open sources was used for Ghent's outside temperature, (Royal Meteorological Institute of Belgium, sd) as a reference temperature. The quarter-hour data was converted into hourly data.

4.1.2. Simulations

Two different simulation environments are used in these analyses: IES VE (IES VE, 2025) and OpenModelica (OpenModelica, 2025). IES VE is more used for whole-building performance modelling and OpenModelica (with the IDEAS library) suits detailed system and control modelling better.

IES VE is a commercial building performance environment where geometry, constructions, internal gains and schedules are defined and transient thermal simulations are run to produce hourly (or sub-hourly) results for zone temperatures, heating/cooling loads, HVAC energy use, ventilation and daylighting. Its integrated modules (Apache, Radiance, airflow tools, etc.) make it efficient for design-stage energy assessment, rapid scenario comparison and sizing of systems, providing time series outputs and visualization suitable for reports and compliance checks.

Dymola is an OpenModelica-based simulation environment that, together with the IDEAS library, enables equation-based, component-level modelling of thermo-fluid systems, heat exchangers, storage and control logic. Models are assembled from reusable physical components connected by ports; the acausal OpenModelica formulation automatically generates the governing differential-algebraic equations and Dymola compiles these into efficient transient simulations. This approach is best for high-fidelity investigation of dynamic interactions, control strategies and component behaviour (compressors, pumps, valves, storage cycling) that cannot be captured in sufficient detail by whole-building tools.

4.1.3. Calculations

The recovery of heat from cooling systems in buildings with continuous cooling demands, like food stores and data centres, has been increasingly applied when a district heating network is accessible. The recoverable heat is transferred into the district heating network.

In this study, the potential benefits of recovering heat on a smaller scale will be investigated, such as for a single house or a few houses connected to a smaller local thermal network, as shown in Figure 20.

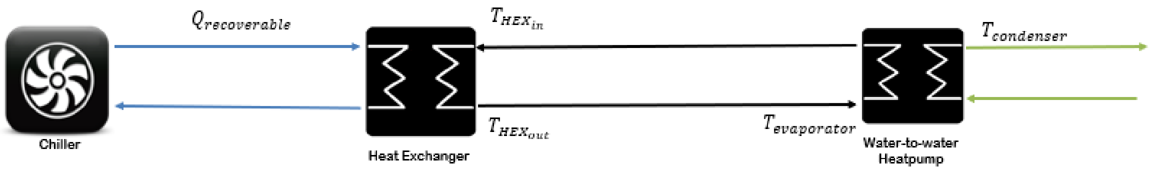

Figure 20: Principle of the local thermal network used to recover heat from a chiller

Hourly profiles of the cooling demand have been created for food stores and small data centres. Because cooling demand depends on specific conditions within each building, which can vary greatly for food stores and small data centres due to the size of the installations, an iteration of the cooling installation size has been carried out.

It is assumed that chillers typically are the main cooling system using the outdoor air to cool the refrigerant. The energy efficiency ratio (EER) at a specific reference temperature is obtained from manufacturer data (Panasonic, 2022). Since the outdoor air cools the system, the corresponding EER at each outdoor temperature is determined on hourly basis using the following formula:

$$EER_{T_{out}} = EER_{T_{ref}} - \left(T_{out} - T_{ref}\right) * EER_{slope}$$

$EER_{T_{out}}$	EER for a specific outdoor temperature
$EER_{T_{ref}}$	EER for the reference temperature
T_{out}	Outdoor temperature
T_{ref}	Reference temperature the EER applies based on manufacturer's data.
EER_{slope}	Slope of the EER per degree Celsius, default value 0,05

Equation 2: Calculation of EER

The heat recoverable on the condenser side of the cooling system is determined by the energy balance of the cooling circuit. According to the Energy Efficiency Ratio (EER = Q_cooling / P_el), the condenser power equals the sum of the cooling power and the electric power consumed by the compressor(s).

The maximum theoretically recoverable heat is the condenser heat, adjusted for the heat exchanger's efficiency, and can be calculated using the following formula:

$$Q_{recoverable} = Q_{cooling} * \left(1 + \frac{1}{EER}\right) * \eta_{system}$$

$Q_{recoverable}$ Amount of recoverable heath (kW)

$Q_{cooling}$ Cooling cacpacity needed during the timeframe in (kW)

EER Energy efficiency ratio for the specific timeframe

η_{system} System losses due to defrost cycles and heath losses, set to 85% as default value

Equation 3: Calculation of condenser recoverable heat

The goal is to maximise the use of the excess heat considering the following limitations:

- The output temperature post-heat exchanger cannot exceed the condenser temperature.
- Not all heat can be transferred due to heat exchanger inefficiencies.

To address these factors, a temperature difference (ΔT) of 5 degrees has been established for the thermal network. The mass flow rate is calculated based on the available cooling capacity of the cooling system, ensuring the ΔT of 5 is consistently achieved. The required mass flow rate is determined using the following formula:

$$\dot{m} = \frac{Q_{cooling}}{C * \Delta T}$$

$\dot{m}$ mass flow (kg/s)

C heat capacity of water, 4186 J/(kg.K)

ΔT temperature difference

Equation 4: Calculation of mass flow rate

Since the heat exchanger output temperature depends on the recoverable heat, which is impacted by the needed compressor energy in a relation to the outdoor temperature, the temperature of the heat exchanger will also differ hourly. The identical mass flow rate is presumed on the output side of the heat exchanger because the same ΔT and a comparable quantity of heat are employed The output temperature was calculated using the following formula:

$$T_{HEX_{out}} = T_{HEX_{in}} + \left(\frac{Q_{recoverable}}{\dot{m} * C}\right)$$

$T_{HEX_{out}}$ Outlet temperature of the heat exchanger(°C)

$T_{HEX_{in}}$ Inlet temperature of the heat exchanger (°C),

Equation 5: Calculation of heat exchanger outlet temperature

After the heat exchanger, the heated water within the thermal network is transported to one or more residential buildings with a heating demand. The supply temperature is however insufficient for the distribution systems, which is why a water-to-water heat pump is used to upgrade this water to the desired temperature.

When the evaporator temperature of the water-to-water heat pump is known, the COP can be determined hourly based on the preferred condenser temperature and the evaporator temperature using the Carnot formula, considering an efficiency factor.

$$COP = \frac{T_{condenser}}{(T_{condenser} - T_{evaporator})} * \eta_{eff}$$

$T_{condenser}$	Condenser temperature (K)
η_{eff}	Efficiency factor to transition from theoretical COP to actual COP

Equation 6: Calculation of COP

5. In depth analyses

This chapter presents the results from the measured/simulated/calculated thorough analysis of the withhold innovative sources with the goal to evaluate their potential in a heritage environment.

5.1. Heat recovery from an attic of a large patrimonial

5.1.1. In situ measurements

Temperature measurements were taken in the Sint-Michiels church. Two sensors were placed in the attic of the church at two different heights, and one sensor in the choir of the church as a reference for the indoor temperature in the church. The measurements were conducted from September 18, 2024, to October 10, 2025. On Figure 21 (next page), data spanning this one year is presented. To clarify the yearly profile, the period from January 1 to September 17, 2025, is displayed at the beginning of the graph.

In the measured data, indoor temperatures are consistently higher throughout the year. Attic temperatures show more peaks compared to the indoor temperature of the church due to increased natural ventilation exchanges, which cause rapid temperature drops, and faster heating from solar radiation in the attic.

Table 9 shows the average temperature of the measured places annually and during the summer months. Annually, the attic temperature averages more than 2°C higher than the outdoor temperature. In the summer months when the heat gain is the highest in the attic, the indoor attic temperature is more than 4.5°C higher than the outdoor temperature. For the meter located slightly higher, no data was available between June 29 and August 6, resulting in the average temperature being just under 3.5°C warmer than the outdoor temperature.

	Average yearly temperature	Temperature difference to $T_{outside}$	Average temperature summer months	Temperature difference to $T_{outside}$
Outside	11,73 °C	-	18,76 °C	-
Attic high	13,79 °C	2,05 °C	23,33 °C	4,57 °C
Attic	13,97 °C	2,23 °C	22,21 °C	3,45 °C
Church inside	14,53 °C	2,80 °C	21,79 °C	3,03 °C

Table 9: Average temperatures of Sint-Michiels attic and church rooms compared to outside

These measurements prove the potential for heat extraction and enhanced efficiencies when the air inside the attics is used as a source compared to the ambient air.

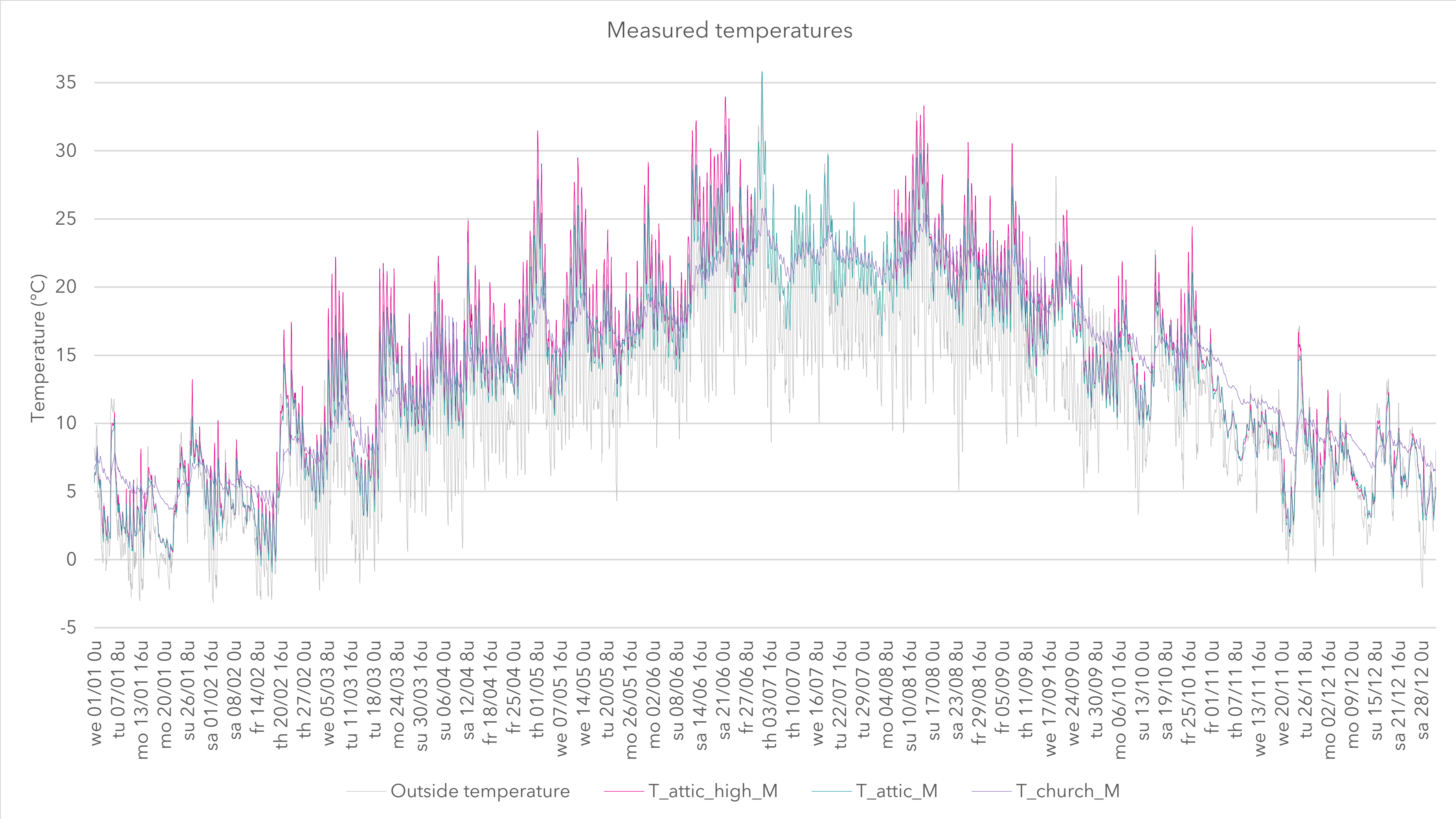

Figure 21: Measured attic and church temperatures of the Sint-Michiels church over one year

5.1.2. Simulation and measurement resemblance

The Attic Heat Recovery Idea was first proven via dynamic simulations after which a measurement campaign in the Sint-Michiels church followed. The measurements were then used to calibrate the initial simulations and obtain more accurate results.

The simulation was further used to estimate the potential heat extraction out of the attic and as a first proof of concept. To model this heat extraction, the attic must be cooled to a certain setpoint temperature. Three different approaches were investigated:

1. A fixed setpoint of 17°C which means that, if the attic becomes warmer than 17°C, heat is extracted until the attic is at 17°C
2. A setpoint equal to the outside temperature
3. A setpoint equal to the outside temperature minus 5 degrees in summer and minus 2 degrees in winter to enhance the heat flux into the attic

The fixed 17°C temperature does come with a trade-off: the lower it is chosen, the more heat can be extracted but the lower the efficiency. More heat can be extracted as the heat flux trough the attic does increase with a larger temperature difference. However, a lower temperature means a lower COP when the heat must be upgraded and the creation of a case in which in summer the outside air might be more of a beneficial source in terms of efficiency.

Trying to extract heat out of the attic as long as the attic temperature is higher than the ambient temperature results in a longer time frame of heat extraction, as the temperature in the attic does not need to reach higher than 17°C before extraction is initiated. However, the simulations showed that a lower absolute heat extraction was obtained (about half of the fixed 17°C setpoint). This is due to the small temperature difference between inside and outside and the low heat influx.

The third option (fixed DT to the outside temperature) causes the highest heat flux throughout the year and reaches about double the heat extraction compared to the first fixed setpoint. However, as the heat is always at a lower temperature than the outside air, the SCOP is lower compared to an ASHP coupled to the ambient air. Therefore, the fixed setpoint method was opted as it provides a middle ground in heat extraction and an enhanced SCOP compared to an ASHP system using ambient air.

Using this setpoint temperature, the Sint-Michiels-church can provide around 96.000 kWh of heat integrated over one year. To put this in relative units: such heat extraction is equal to **47,4 kWh/m³attic or 137,5 kWh/m²attic**. These values can serve as a benchmark for other patrimonial attics. This system allows to reach an average SCOP of 5,2 which is considerably higher than an ASHP using ambient air (SCOP 3,55). However, it must be mentioned that the attic will mainly provide heat from late spring to early autumn (otherwise the attic is colder than 17°C), which coincides with lower building heat demands. Besides, in this timeframe, an ASHP using ambient air does also reach its highest COP values. If the SCOP of an ASHP would be considered in only this timeframe, a higher value can be obtained.

5.2. Heat recovery from densely populated spaces

Densely occupied urban spaces such as fitness centres, sports halls and entertainment venues are a largely untapped source of low-grade thermal energy. High occupant density produces significant sensible- and latent heat that, with heat recovery systems can be captured and reused for hot water, space heating, pre-heating ventilation air or fed into local district heating networks. Typical challenges are the highly variable occupancy and thermal loads, the need to maintain strict air quality, and integration with existing HVAC and urban heat networks. With smart controls, thermal storage and coordinated planning at neighbourhood scale, these lively city spaces can become reliable, resilient contributors to circular urban energy systems, in theory. To test these assumptions, a dynamic simulation was performed.

5.2.1. Simulation

The simulation model was built in the IES VE software. It is based on an existing building that contains both a sports hall and an event venue. The model can be seen on Figure 22. In basis, some standard insulation values, heating and cooling setpoints and internal gains were chosen to assess the potential. The basis case does have cooling and heating systems and adequate capacity to provide comfort. Three variants were simulated apart from this basis case. These variants are:

- No cooling: how much cooling can be provided if the fitness/venue does not have any cooling system, the only cooling that can be provided is via the ventilation air
- Bad building envelope: this variant evaluates the effect of an old building with low insulation levels
- No windows: this last variant looks at the effect of the windows and the solar heating, more specifically the absence of windows

Table 10 summarises the cooling loads in the different cases. The left most columns represent the cooling loads over the whole year, the right most columns only look at the period October-May when most buildings typically require heating. The rows represent the different variants. The fitness was modelled at 1.420 m², the venue is much smaller (meeting room venue) at 130 m².

	yearly		**October-May**	
	Venue	_Fitness_	_Venue_	_Fitness_
Basis	20,88 kWh/m²	18,78 kWh/m²	2,68 kWh/m²	2,46 kWh/m²
No cooling	8,03 kWh/m²	3,48 kWh/m²	0,66 kWh/m²	0,26 kWh/m²
Bad building envelope	13,58 kWh/m²	19,95 kWh/m²	0,80 kWh/m²	1,78 kWh/m²
No window	8,04 kWh/m²	9,39 kWh/m²	0,66 kWh/m²	0,59 kWh/m²

Table 10: Cooling loads of densely populated spaces in different scenarios over one year

As can be seen, the heat loads are rather minor in all cases and especially when looking at the relevant period between October and May. The simulations indicate some potential for heat recuperation, be it minor.

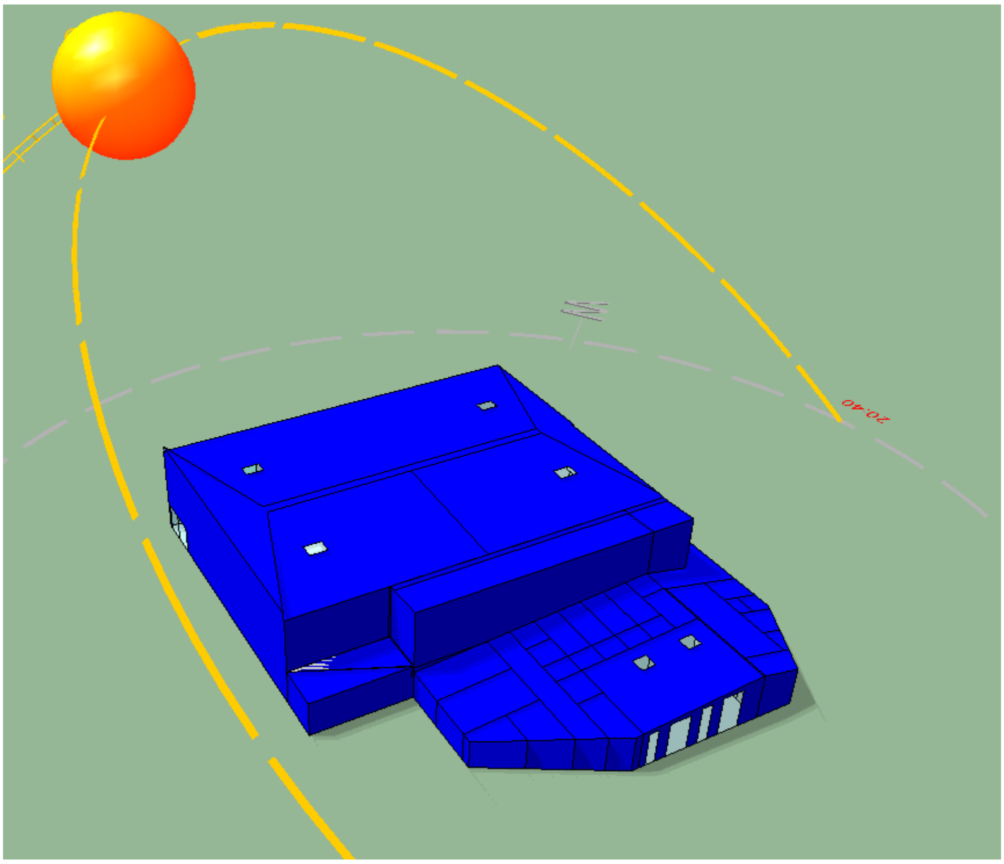

Figure 22: Simulation model for densely populated spaces

5.3. Heat recovery from food chains

Five profiles are representing the cooling demand in food stores of various sizes. Table 11 shows the capacities and their respective EER based on manufacturer data (Panasonic, 2022) at a reference condenser temperature of 35°C and evaporator temperature of 7°C, conform norm EN14511. Additionally, the necessary mass flow is provided for these powers at a ΔT of 5 degrees.

Scenario	Cooling demand (kW)	EER	Mass flow (kg/s)
1	50	3,12	2,39
2	60	3,05	2,87
3	75	2,93	3,58
4	100	3,00	4,78
5	150	3,26	7,17

Table 11: Cooling demand in food stores of various sizes with the respective energy efficiency ratio and needed mass flow

A load profile for the cooling demand in the food store has been established, considering night reduction outside the store's opening hours due to lower internal heat gains. The profile is shown on Figure 23.

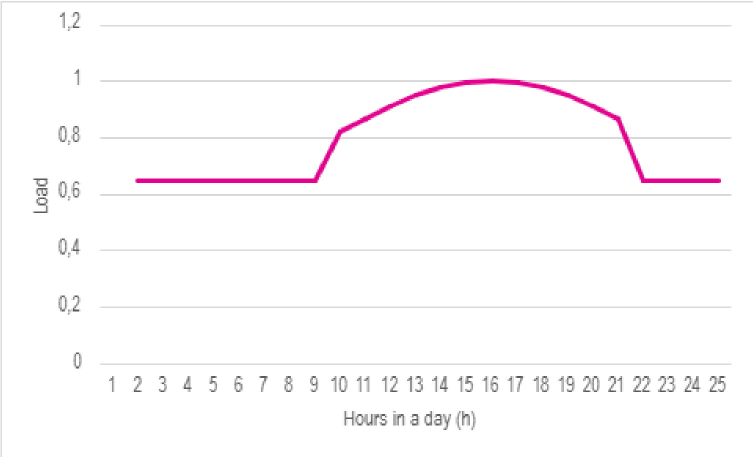

Figure 23: Hourly profile of the cooling demand in percentage

From this data, an hourly profile of the annual cooling demand is compiled for each scenario. The amount of recoverable heat is calculated according to the methodology.

This calculation assumes a condenser temperature of 35°C for the cooling system, representing a compromise between the efficiency of the cooling system and the usability of the recovered heat (Figure 20). Higher temperatures would result in increased condenser pressures and reduced compressor efficiency, while lower temperatures would limit the available useful heat. The outlet temperature of the heat exchanger is therefore limited to this temperature.

It is further assumed that the efficiency of the heat exchanger is 85%. With a ΔT of five degrees, the input temperature from the thermal network to the heat exchanger is 24°C. For simplicity, this temperature is considered constant.

Figure 24 displays the thermal network temperature after the heat exchanger used by the water-to-water heat pump as source, corresponding to various heat recuperation capacities. The outdoor air temperature is also shown what would be used as a heat source of a traditional air-to-water heat pump, serving as a reference point if no heat would be recovered from the chillers of the food chains .

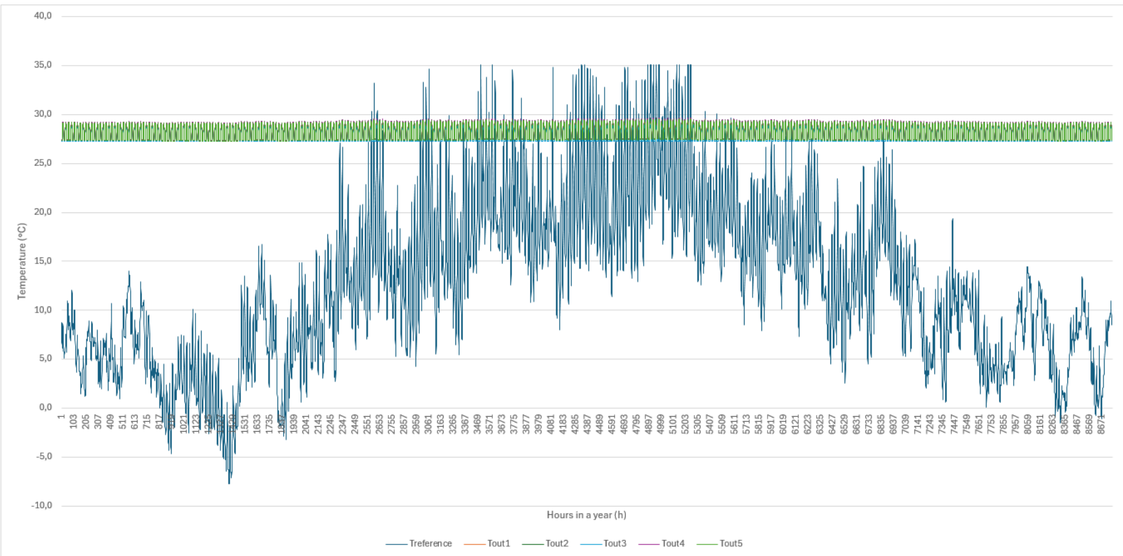

Figure 24: Source temperature for the different scenarios and the reference scenario

Figure 25 shows the COP of each scenario at a desired temperature regime of 45°C. Due to inefficiency during the heat transfer, a condenser temperature of 48°C is required. The identical approach has been used for the evaporator temperature, with 3°C deducted from the supply temperature.

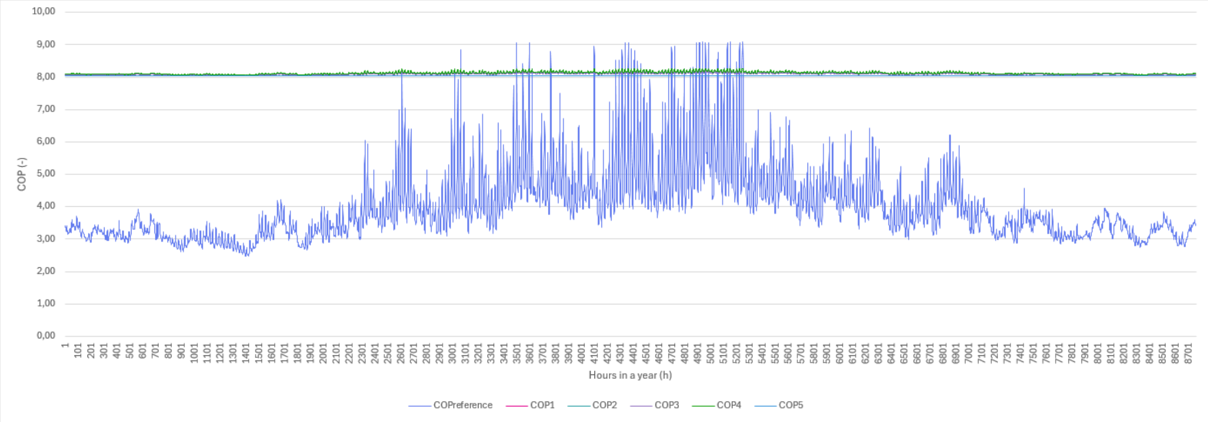

Figure 25: COP of each scenario for every hour of the year, same temperature requirements

The heat recovery from continuous innovative thermal energy sources yields a higher Coefficient of Performance (COP) than traditional heating systems. The benefits from continuous sources primarily depend on installation size. Therefore, an overview of electricity consumption for these continuous energy sources is provided for the heat demand in both the pre-renovation and renovation baseline scenarios.

Table 12 shows the electricity consumption when recovering the heat form food stores. As a reference, the consumption using an air-to-water heat pump at a temperature of 45 degrees is provided. The reduction in electricity consumption is also noted when compared to traditional heat pumps.

	Heat demand (kWh)	
Pre-renovation scenario	*19.978*	
	Electricity consumption (kWh)	*Reduction*
Air-to-water heat pump	*6.107*	
Heat recovery from food chains	*2.548*	*-58%*

	Heat demand (kWh)	
Renovation scenario	*11.210*	
	Electricity consumption (kWh)	*Reduction*
Air-to-water heat pump	*3.439*	
Heat recovery from food chains	*1.431*	*-58%*

Table 12: Financial savings of heat recovery from food stores on household level

5.4. Heat recovery from micro & small datacentres

Hourly load profiles for heat recovery from data centres were developed in the same manner as those for heat recovery from food stores. In this case the hourly profiles are constant and scaled with the number of servers. A heat dissipation rate of 500 W per server and 20 servers per rack were assumed. The cooling demand was calculated for a different number of racks representing server rooms ranging from small office buildings to larger office buildings. For the lower cooling demands until 20 kW, it is assumed CRAC's are used with an general EER of 3,5 for a condenser temperature of 35°C and evaporator temperature of 7°C (norm EN14511). For higher cooling demands CRAH's would normally be used. At this stage, the heat recovery efficiency is considered the same for both systems. Table 13 presents the characteristics for a few number of cases.

Scenario	Number of racks	Cooling demand (kW)	EER	Mass flow (kg/s)
1	0,5	5	3,50	0,24
2	1	10	3,50	0,48
3	2	20	3,50	0,96
4	5	50	3,12	2,39
5	25	250	3,26	11,94

Table 13: Cooling demand for datacentres of various sizes with respective energy efficiency ratio

An hourly profile has been developed for the data centres, in the same way as was done in 5.3 Heat recovery from food chains. The same parameters have been applied. There is less variation in the demand profiles compared to food stores because the demand profile is continuous for dedicated server cooling systems in office buildings. Other internal heat gains beside the servers themselves have minimal impact in the closed server rooms. These profiles can be seen below; Figure 26 and Figure 27 present the source temperature and COP values for each scenario over one year, respectively.

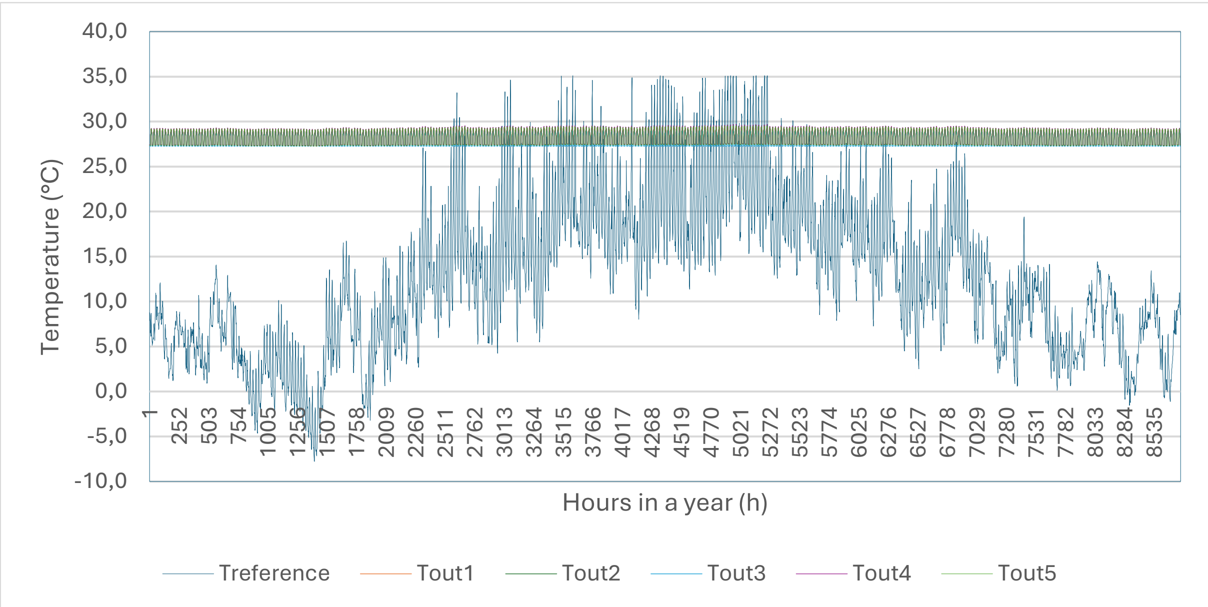

Figure 26: Source temperature for the different scenarios and the reference scenario

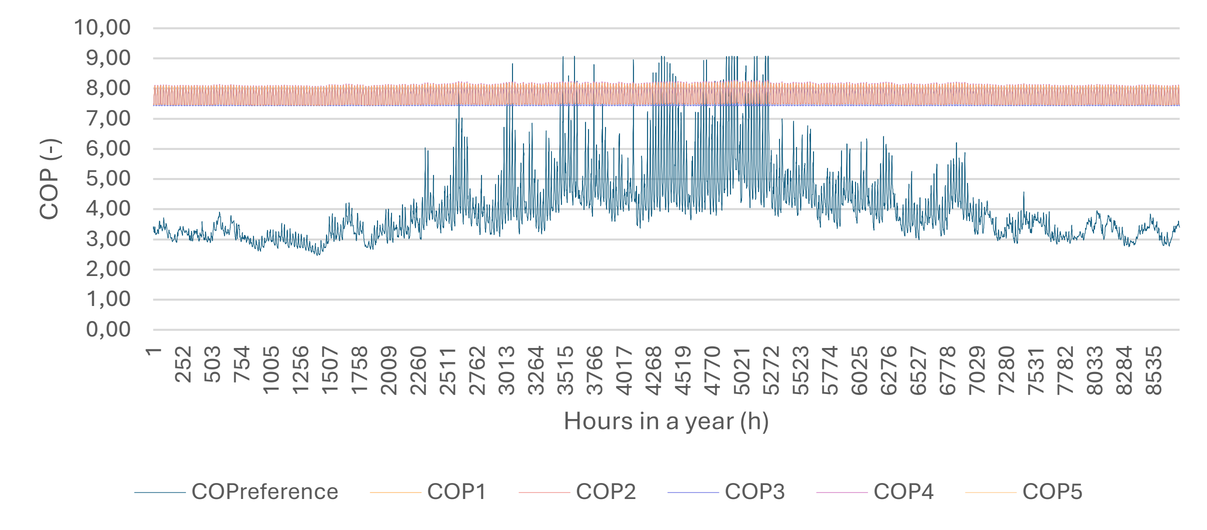

Figure 27: COP of each scenario for every hour of the year

The COPs are applied on an hourly basis for the demand profiles for the pre-renovation and renovation baseline and compared with the air-to-water heat pump. Table 14 uses these COPs to obtain financial savings, as can be seen below.

	Heat demand (kWh)	
Pre-renovation scenario	*19.978*	
	Electricity consumption (kWh)	*Reduction*
Air-to-water heat pump	*6.107*	
Heat recovery from datacentres	*2.476*	*-59%*

	Heat demand (kWh)	
Renovation scenario	*11.210*	
	Electricity consumption (kWh)	*Reduction*
Air-to-water heat pump	*3.439*	
Heat recovery from datacentres	*1.389*	*-59%*

Table 14: Financial savings of heat recovery from datacentres on household level

5.5. Heat recovery from ventilation in underground structures

5.5.1. In situ measurements

Similar measurements to those taken at the church in Ghent have been conducted at the underground parking facility 'Sint-Michiels' in the Sint-Michiels case study neighbourhood, as described in Section 5.1.1.

The measurements were conducted from September 18, 2024, to October 10, 2025. In the graph below, data spanning this one year is presented. To clarify the yearly profile, the period from January 1 to September 17, 2025, is displayed on Figure 28.

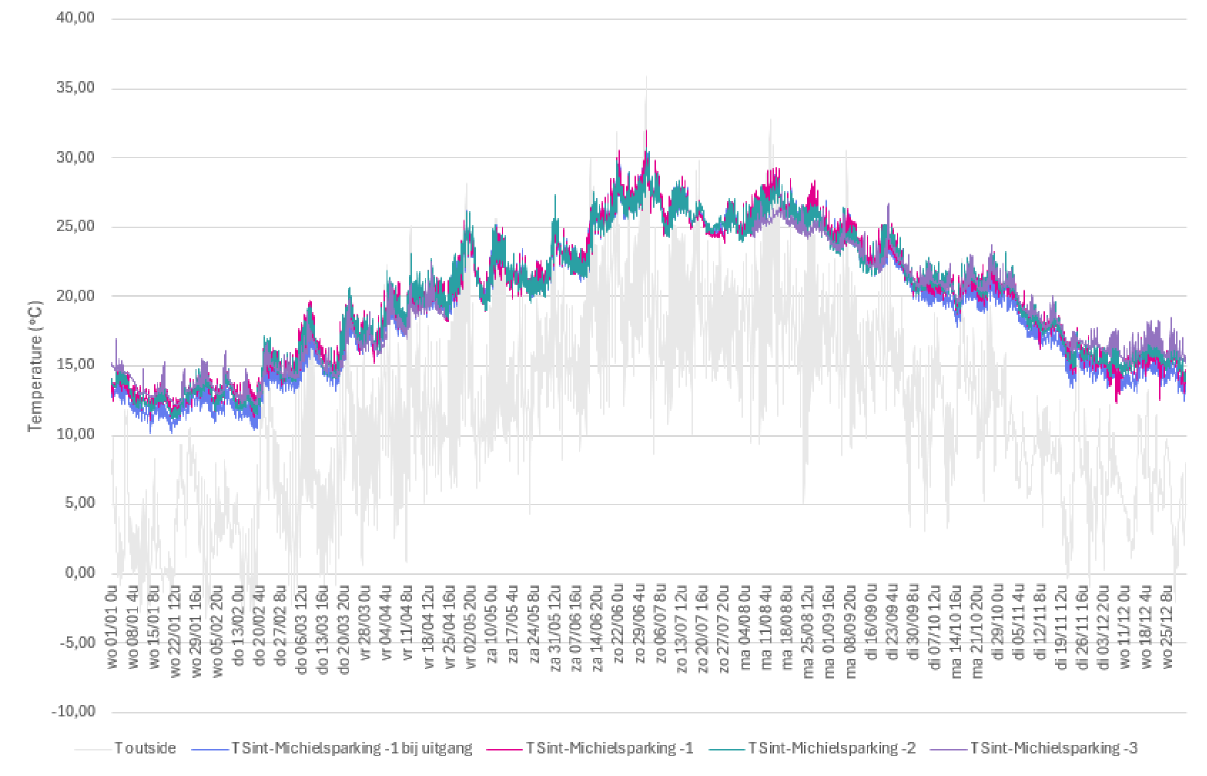

Figure 28: Measured parking floor temperatures of the Sint-Michiels parking over one year

The underground floor -3 has a higher temperature during the winter months compared to the temperatures found on the other underground floors. Conversely, during the summer months, the temperature at floor -3 is notably lower than the other floors. This data highlights that the deeper the floors are located, the greater the buffering capacity of the surrounding soil, which allows for more stable and consistent temperatures at greater depths.

Overall, the underground floors maintain a temperature that is consistently higher than the outside temperature, except during instances of peak heat. This pattern illustrates distinctive seasonal temperature variations across different floor levels.

The table below displays the average annual temperature for outdoor air and various measuring points, along with the temperature differences compared to the outside temperature. The highest temperatures occur at levels -1 and – 2. Level -3 shows a smaller difference from the outside temperature due to lower temperatures in the deeper floors during summer.

Average temperatures for December, January, and February are provided, highlighting the need for heating in winter. The temperature difference is significantly higher during these months compared to the outside temperature. In these months, the lower levels are warmer, as can be seen in Table 15

	Average yearly temperature (°C)	**Temperature difference to $T_{outside}$ (°C)**	**Average temperature winter months (°C)**	**Temperature difference to $T_{outside}$ (°C)**
Outside	11,73	-	4,64	-
Floor -1 near exit	19,53	7,79	13,03	8,39
Floor -1	20,03	8,29	13,95	9,32
Floor -2	19,96	8,22	13,95	9,32
Floor -3	18,30	6,56	14,56	9,92

Table 15: Average temperatures of Sint-Michiels parking floors compared to outside

5.5.2. Calculations

The Sint-Michiels parking measurements mentioned above serve as an example for calculations. The exact ventilation flow rate of the underground parking is unknown. The facility contains 465 parking spaces. Leefmilieu Brussels sets a minimum air flow of 200 m³/h per parking space (Leefmilieu Brussels, 2022). According to Buildwise (Buildwise, sd), the standard NEN 2443 necessitates a flow rate of 3 m³/s per m² of surface area. For the Sint-Michiels parking, this translates to an airflow rate between 81.600 m³/h and 93.000 m³/h.

Additionally, the parking manager stated that there is no heat recovery system in place, and the mechanical ventilation operates continuously at a reduced flow rate. The lowest flow rate considered corresponds to approximately 1 air change per hour (ach), which accounts for 1/4 of this base rate (23.250 m³/h) is used for the calculations. A higher ventilation rate would result in lower indoor temperatures, resulting in a lower heat recovery capacity.

In this application, it is assumed that the extracted ventilated air serves as the heat source instead of outside air. Thus, the system is designed similarly to a ventilation heat pump. Heat recovery can be achieved by:

- Placing the evaporator of the heat pump in the extraction duct
- Using an air-to-air heat exchanger
- Providing a thermal buffer via an air-to-water heat exchanger

In this calculation, the extraction temperature is equated to the heat source. For the COP calculation, the evaporator and condenser temperatures are adjusted by +3°C and -3°C, respectively, to reflect that not all heat is absorbed or released. The condenser temperature is set to 48°C to ensure a delivery temperature of 45°C for the delivery systems.

The COP for both the ventilation heat pump and the conventional air-to-water heat pump with outside air as the heat source are included in Figure 29 for the temperatures during the measurement period.

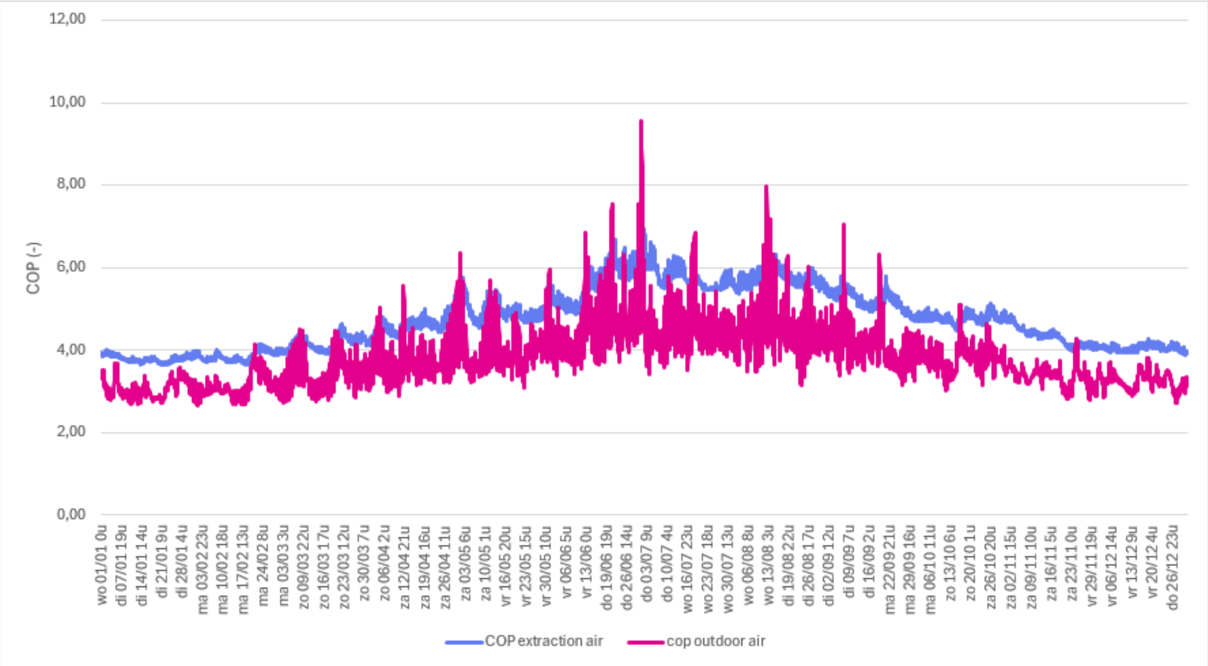

Figure 29: Comparison of COP of a heat pump coupled to parking exhaust air versus outside air

The average COP with ventilation air as a heat source is 4,76, which is 25% higher than the COP with outside air as a heat source of 3,81.

5.6. Heat recovery panels in underground structures

Underground car parks represent a consistent, under-utilised low-temperature heat source. Heat recovery panels mounted on ceilings or walls can harvest this waste heat from warm surfaces and the ambient air, transferring it to a fluid loop that feeds heat pumps or local space-heating circuits. Because car parks are in the underground, used continuously and often ventilated, they provide a stable, year-round heat supply that is largely independent of outdoor weather.

The recovered heat is typically low-grade, so integration with a heat pump is required to raise it to useful temperatures for building heating or domestic hot water. System performance is rather independent on parking occupancy or ventilation strategy as most heat comes from the ground to which the panel is mounted.

The panels provide a hybrid solution to expensive geothermal systems: they utilise the same stable ground as heat source and avoid the high drillings costs as they utilise already build car parks. Simulations using the OpenModelica environment were carried out to estimate the heat recovery potential.

5.6.1. Simulations

Heat transfer between the ground, walls, air, and panels is modelled in one dimension. This simplification is justified for this application, as the primary of heat transfer is perpendicular to the panels, while heat transfer in other directions is expected to be minimal. The different components, such as the walls and the ground, are modelled as single units, which is called a lumped-element model. Since this study aims to evaluate the general feasibility, a simple yet reliable model is preferred. This allows for long-term simulations of the heat that can be extracted per panel and the impact on the temperature of different components. This work elaborates on the model prepared by the KUL (Vandenhout & Ulens, 2025)

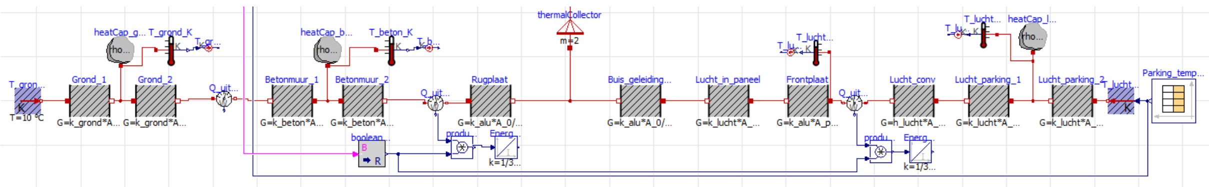

Figure 30: OpenModelica RC model of the ground and air

This one-dimensional thermal model is implemented as an RC-model, using thermal resistances (R) and capacitors (C). The resistances represent heat transfer pathways, while the capacitors represent the capacity to store heat. Figure 30 illustrates the schematic RC-model of this situation. In the model, a fixed ground temperature is assumed at a certain distance. Heat transfer occurs through different thermal resistances, those of the ground, wall and backplate, together with a thermal capacitor of the ground and wall.

In parallel, the air volume inside the parking is considered. Here, the heat flows through the thermal resistance of the air, the aluminium front plate and the pipe through which the water itself flows, along with a thermal capacitor C of the air. The measured air temperature was used as the 'far' air temperature that will not be influenced by the panel dynamics.

The case study uses the underground car park in Ghent near the Sint-Michiels-Church measuring 40 × 40 m with three storeys of 3 m height. The base RC model was extended into a heat extraction model by adding a simple passive cooling system that switches on/off according to historical outdoor temperature data. When the outside temperature exceeds 18 °C, passive cooling is activated and the ground is regenerated. The models thus both facilitates heating and cooling.

Figure 31 represents the whole model. Besides the RC ground & air model, the panel itself can be observed as a pipe between two water sources. It is assumed that the water always enters the pipe at the same temperature (apart from when passive cooling is activated). The added energy can be calculated via the temperature difference over the pipe. The other components are used for control and result processing.

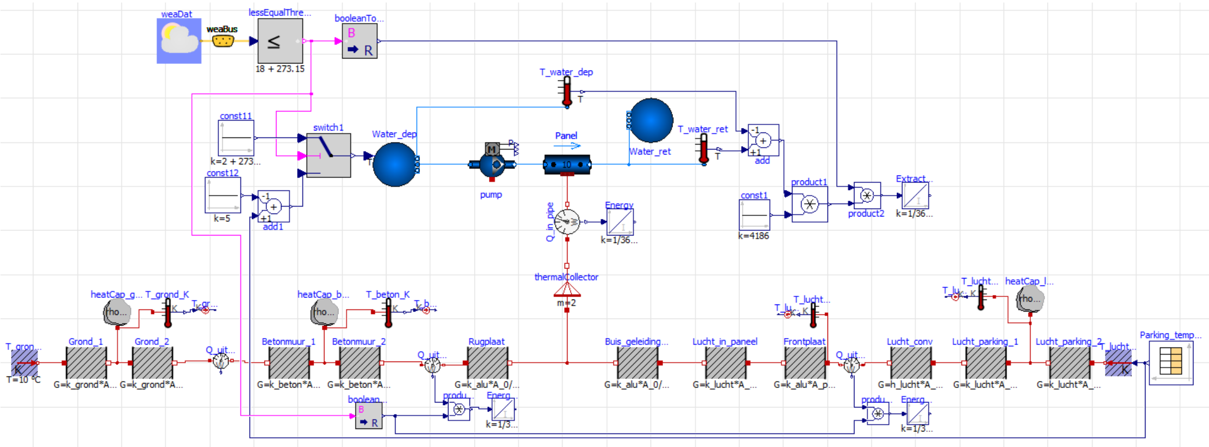

Figure 31: Complete OpenModelica model for the car parking panels

Table 16 summarises the results for one panel which coincides with the results per square meter. Figure 32 represents the extracted power and energy for one panel over one year. From early spring until late autumn the power drops to zero which is due to active passive cooling. This active cooling does cause the temperature of the ground and wall to rise again and almost reach its starting temperature after one year, as can be seen on Figure 33.

Average power	64,2 W
Extracted energy	470,5 kWh
Share of energy from air	19,3 %
Share of energy from ground	80,7 %

Table 16: Summary of results for one panel or 1 m² panel

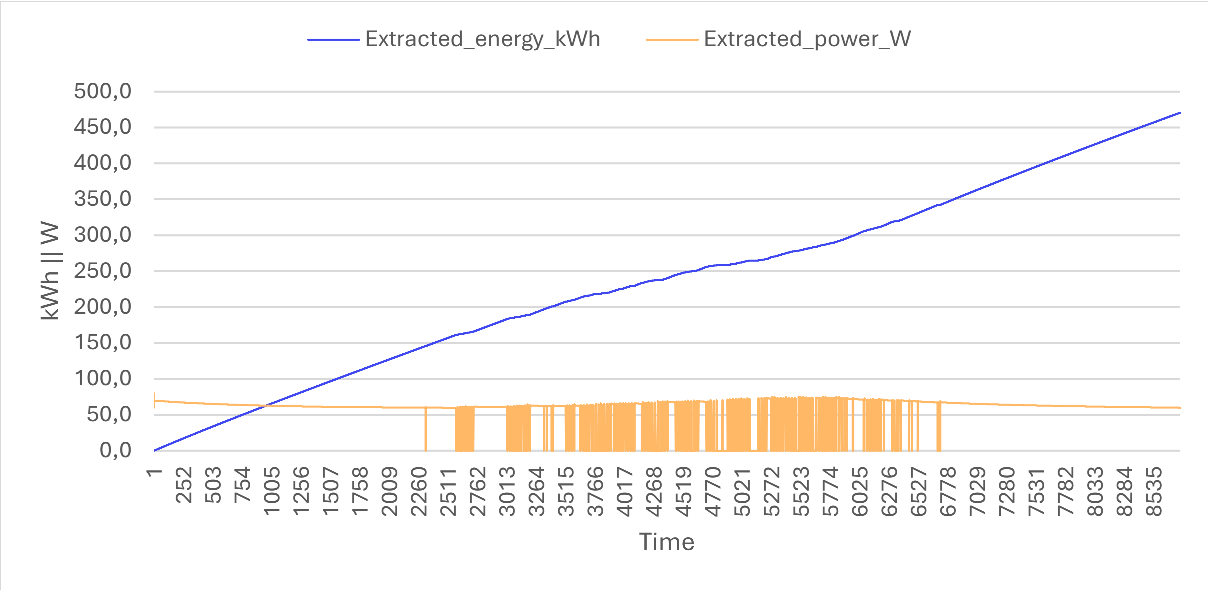

Figure 32: The extracted power and energy over one year for one panel

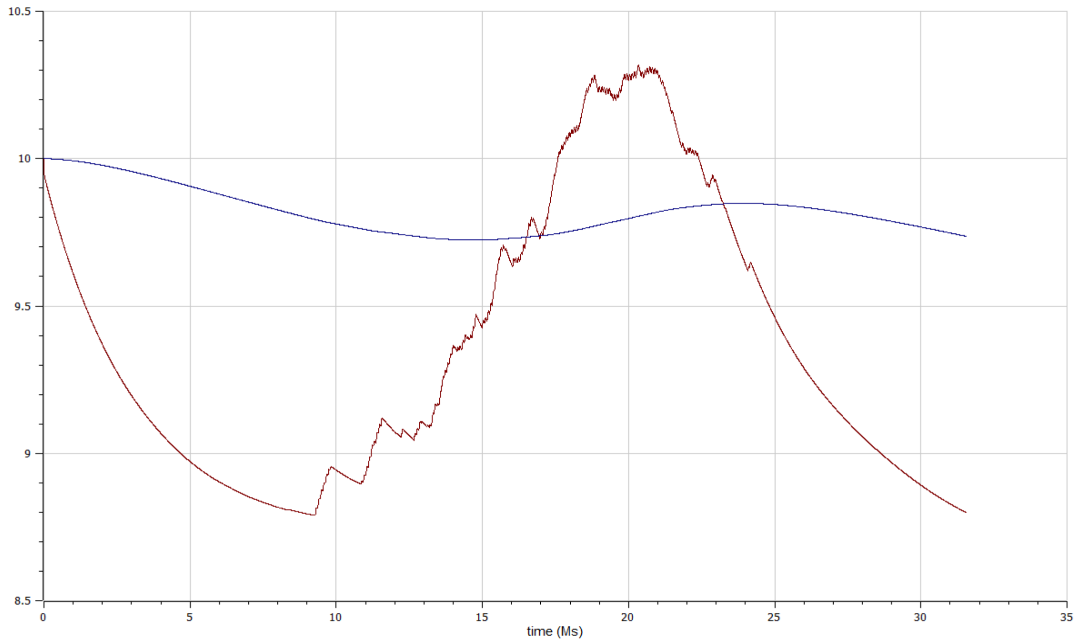

Figure 33: Ground (blue) and wall (red) temperature throughout the year

5.7. Solar thermal energy from squares, cycle lanes and open spaces

Solar-exposed urban surfaces – squares, cycle lanes and other open spaces – represent a largely untapped source of thermal energy. By integrating asphalt solar collectors or networks of heat-exchange tubes directly into pavement layers, sunlight absorbed by dark surfaces can be captured as low-grade heat and recovered. Such pavement collectors make use of existing urban footprints without occupying additional land, reduce surface temperatures (mitigating urban heat island effects), and can improve winter road safety when used for de-icing.

Practical potential depends on site-specific factors: solar exposure, pavement area, insulation and thermal coupling to the ground, tube layout and flow rates. Technical challenges include durable integration into traffic-bearing surfaces, maintenance access, water-tightness, freeze protection, and efficient heat pumps or buffer systems to upgrade the low-grade heat. Considering all above-mentioned points, they prove a promising technology that can be integrated in a multilayered energy system to provide heritage neighbourhoods.

5.7.1. Calculations

The possible energy extraction was calculated using hourly solar irradiance files obtained via PVgis (Commission, Photovoltaic geographical information system, 2025). As the solar irradiance is the main dynamic playing a role (no shadow was assumed), the energy can be calculated using only this input. Based on literature data, the efficiency of these systems was estimated and used to convert incident irradiance into the energy inside the asphalt collector. Figure 34 presents this irradiated and extracted power throughout the year. When integrating this power, the energy potential for this concept can be obtained: **276,8 kWh/m²asphalt**.

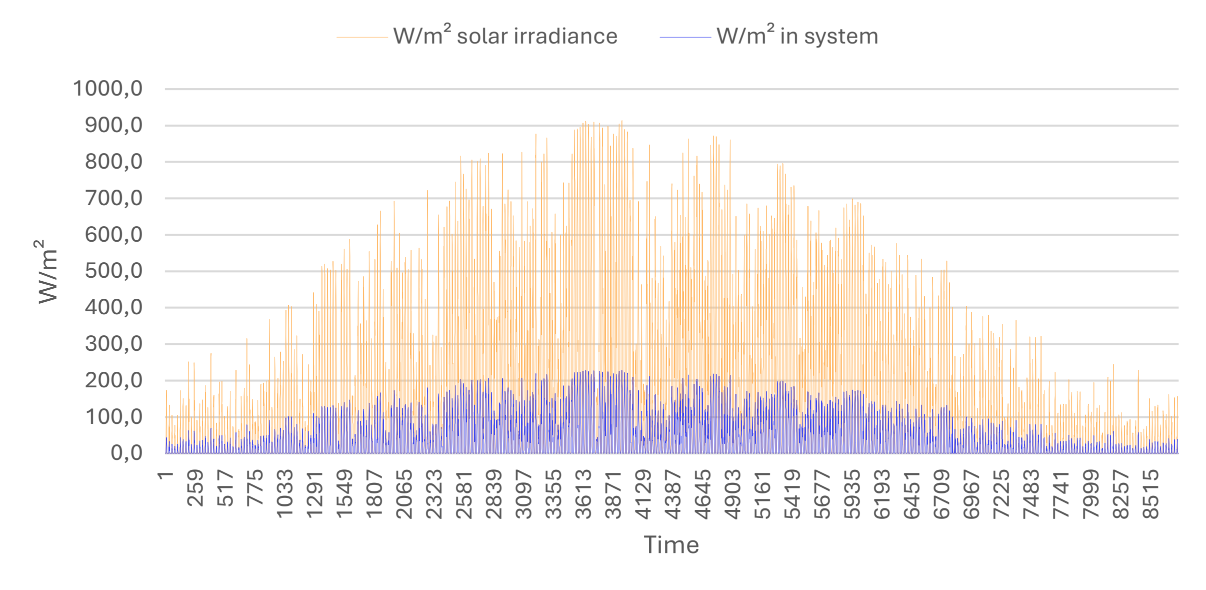

Figure 34: Solar irradiance and extracted power over one year per m² asphalt collector

5.8. Vibration energy harvesting

Piezo electric floors generate energy from vibrations and have a limited power per square meter. Existing panels provide 35 Wp/m², but their need for constant movement is the main issue. In historical city centres, densely populated open areas spread crowds over larger spaces, necessitating panels that cover extensive areas. Installing piezo electric (PE) panels on a large scale requires significant investments and would yield limited returns. The focus should therefore be on busy places where people pass frequently. One possible example within a historic centre is the entrance of a station.

Figure 35 shows a simplified calculation of the yield that can be generated at the Gent-Sint-Pieters train station, located in the case-study neighbourhood Ghent, Belgium. This station has an average of 48.885 visitors on a weekday and 23.575 visitors on a weekend day (NMBS, 2024). To determine the yield, the number of visitors is distributed over an expected hourly profile.

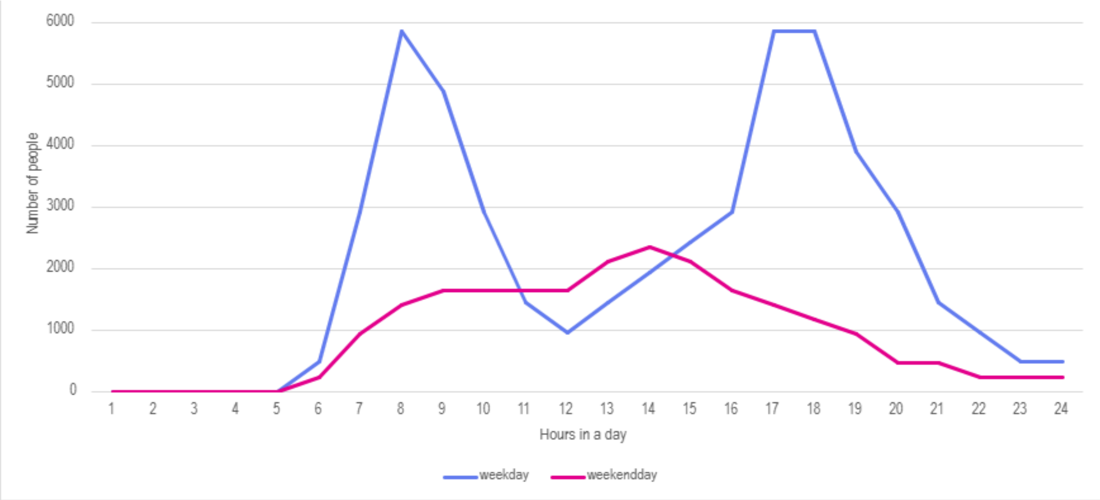

Figure 35: Hourly number of passengers through Gent-Sint-Pieters station (NMBS, 2024)

The theoretical yield was determined for 24 panels of 1x1 meter at the main entrance of the station. This entrance is 8 meters wide, resulting in a panel structure of 8x3 and a possible peak power of 0,84 kWp. To calculate the yield, it is estimated that 75% of visitors use this entrance, the 8 panels in each row are used equally frequently, and it takes a person an average of 2 seconds to walk over the whole installation.

The yield of the same area of solar panels with a power of 210 W/m², totalling 5.04 kWp, is provided for reference. The yield of the PV panels is determined via PVgis (Commission, Photovoltaic geographical information system, 2025) based on data from 2023.

Table 17 shows that the yield of solar panels is higher than piezoelectric panels. The same surface area of PV panels generates 5.320 kWh, while PE panels generate 678 kWh. South-facing PV panels produce thus more than 7,5 times the yield of PE panels. This is expected since the power per m² is higher for PV panels. Additionally, the efficiency of PV panels, at 1.056 kWh/kWp, is higher than 807 kWh/kWp for PE panels. Currently, the costs are significantly higher for piezoelectric panels at €31.250/kWp compared to €1.100/kWp for PV panels. Figure 36 shows this comparison of the yield graphically.

It can be concluded that currently, Piezo systems will not be utilised apart from very niche applications.

Panel	Yield (kWh)	Efficiency (kWh/kWp)	Estimated costs
Piezo electric	678	807	€ 26.250
Photovoltaic	5.320	1.056	€ 5.544

Table 17: Comparison of piezoelectric and photovoltaic yield

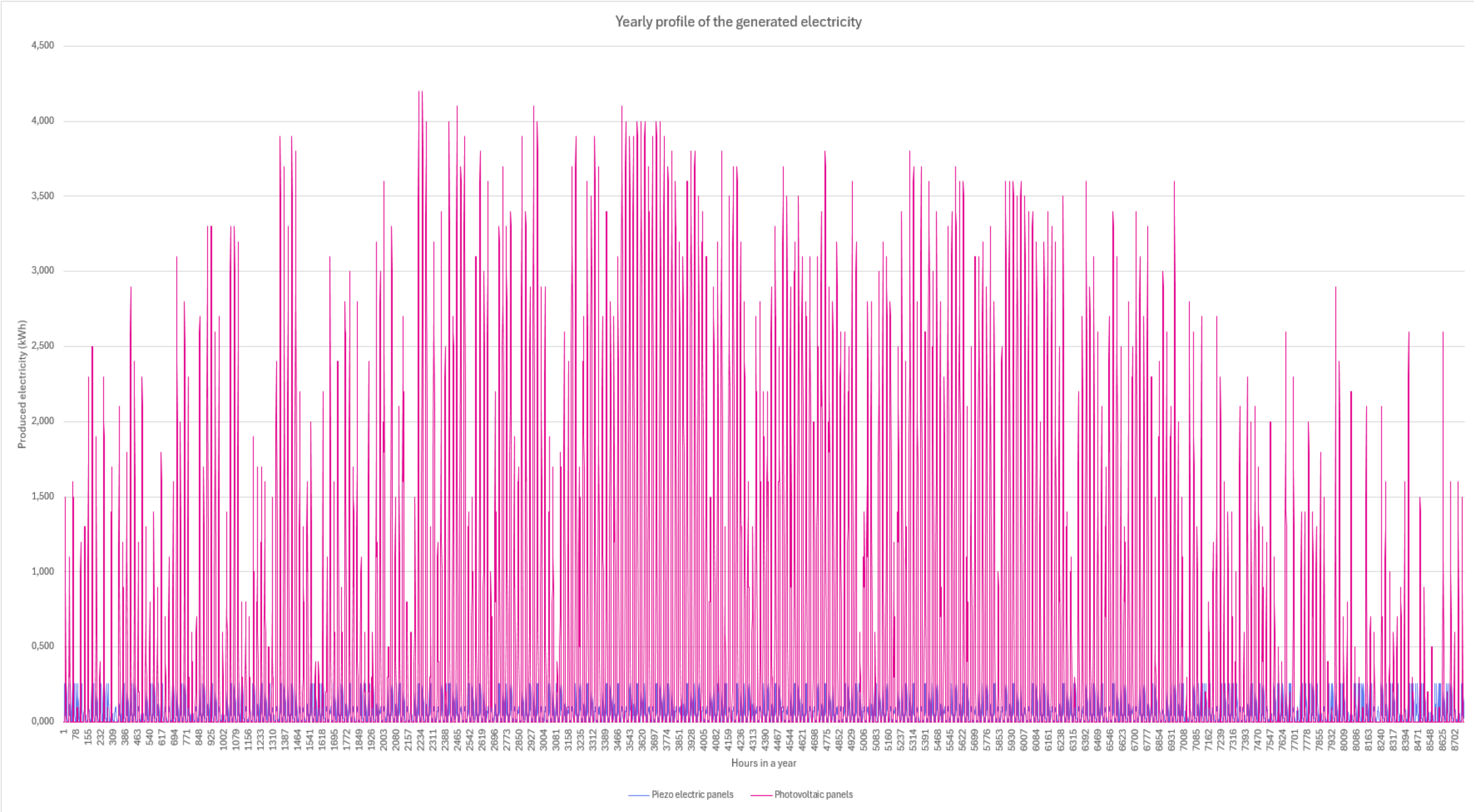

Figure 36: Comparison of piezoelectric and photovoltaic yield

6. Results

In the previous chapter, an hourly supply and temperature profile was calculated/simulated for each innovative source for one year. To allow for a fair comparison, all innovative sources will be matched to demand profiles to assess their suitability to a heritage context. For this demand file, an hourly profile was constructed for the pre-renovation and renovation baseline scenarios for one household. For the neighbourhood level, a demand file was constructed that represents 32 heritage households. Five KPIs were used to assess how well the demand and the supply of the different innovative sources match. These five KPIs allow to make a proper comparison between the different sources. Finally, a financial analysis was conducted in which all sources were compared to a reference system that consists of only air-source heat pumps to supply the household/neighbourhood.

6.1. Demand profiles

To allow for a fair comparison, all innovative sources will be matched to different demand profiles to assess their suitability to a heritage context. Three profiles will be constructed: pre-renovation household, renovation household and neighbourhood level. It is important to note that the temperature regimes required to provide comfort differ between the different demand profiles. In this report, a general temperature of 45°C was assumed as supply temperature. Higher temperatures will be provided decentral and are not considered as they will be required in all cases. More detail on the profiles can be found in the text below.

6.1.1. Building level

The hourly profiles created for each innovative heat source are compared with the demand profiles of a case study building for two different scenarios. More information can be found in deliverable D5.4. For convenience, they are summarised here:

- **Pre-renovation scenario:** The pre-renovation baseline describes historic Belgian townhouses mostly used as single-family dwellings (except the multi-family townhouse) with attics and basements generally unconditioned and used for storage or technical space. Their envelopes are uninsulated solid masonry with largely original interior lime plaster and varying window/airtightness states. Space conditioning relies on central high-temperature hydronic heating with thermostatic radiator valves and on/off central control, no mechanical ventilation or cooling, and gas boilers (single or per-apartment) plus localized electric DHW in some setups, with no solar PV or storage.
- **Renovation scenario:** The renovation baseline assumes upgrades meeting contemporary Flemish energy rules while taking heritage exemptions for façade and windows into account that limit interventions. Buildings are thermally upgraded where permitted (insulating rear/annex walls, roofs and ceilings, replacing rear windows), yielding improved airtightness. Space conditioning keeps central hydronic heating (lower supply temperatures, retained or new high-temperature radiators), added mechanical ventilation with heat recovery, and energy systems move to high-efficiency condensing gas boilers, continued localized electric DHW and a limited PV installation.

Figure 37 shows the space heating demand profiles for these two scenarios. In the Pre-renovation scenario, peaks exceed 30 kW. For visual clarity, the heat demand in the graph is capped. DHW is not included in these heating profiles as the pre- and renovation baseline scenario define DHW being produced local via electric boilers.

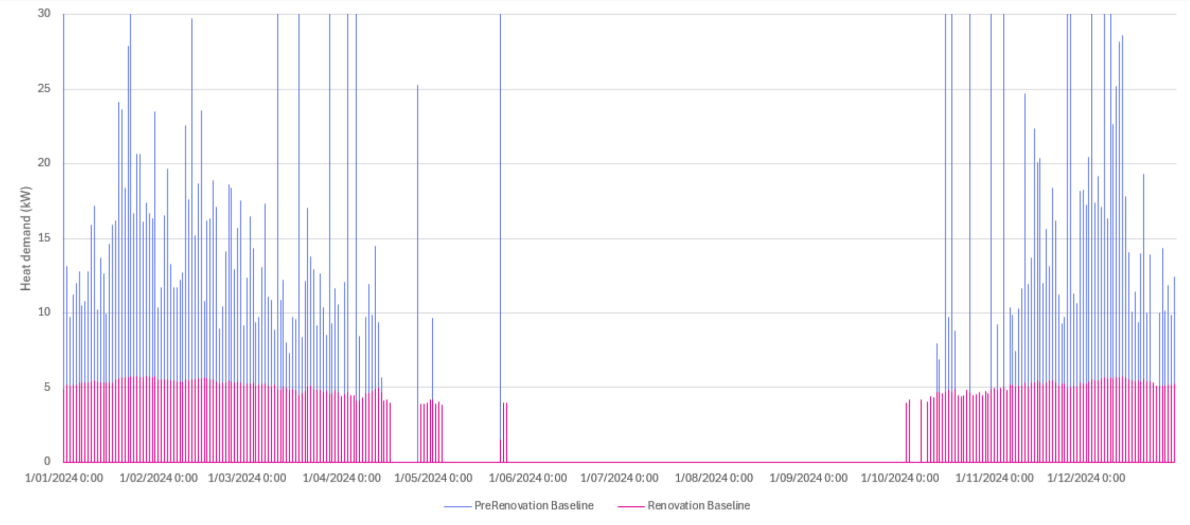

Figure 37: Demand profiles for one pre-renovation- and one renovation household

6.1.2. Neighbourhood level

For all cases, a resulting hourly file for the potential recovered heat was obtained. If the source is thermal, an hourly file of the temperature at which this heat can be extracted is obtained too. To investigate how well suited a source is in a heritage context, the hourly supply file is matched with a demand file. For this demand file, an hourly profile was used from a reference project that represents 32 heritage renovation households in the city of Bruges. Again, only the space heating is considered as the baseline scenario's, defined in D5.4, define DHW locally produced using electricity. Figure 38 presents this profile.

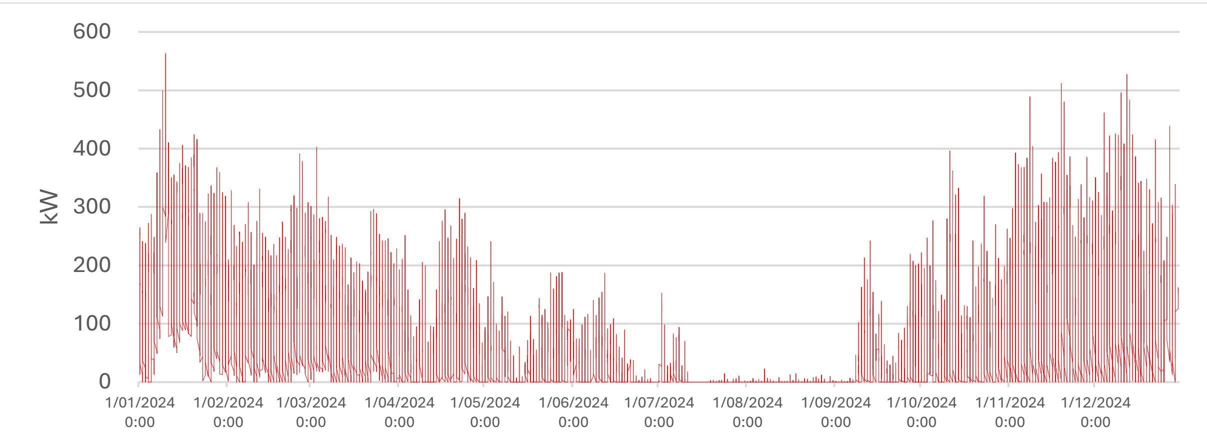

Figure 38: Space heating profile for heritage neighbourhood (560 kW peak, 830 MWh/y)

As mentioned, the supply temperature of the heating network will be at 45°C, which results in a SCOP equal to 3,55 for an ASHP system as reference.

The temperature file is used to evaluate if the source provides the heat more effectively than a reference air source heat pump that uses the outside air. A total of five KPIs were selected to evaluate the sources relatively against one another. They can be found in Table 18.

Parameter	Explanation
Profile match	Presents the percentage of how much of the space heating demand profile can be supplied directly by the source on an annual basis.
Absolute match	Presents the percentage of the total heat demand that can be supplied by the total heat recovered by the source if a storage is included (assuming no heat losses).
Source match	The profile match divided by the absolute match. This parameter thus shows how adapted the source already is to a heritage demand. If most heat can already be supplied directly, a high percentage is obtained.
COP enhancement	This percentages shows how much higher (or lower) the SCOP of the innovative source is compared to an ASHP, assuming a set temperature to which the heat should be delivered and only evaluating both sources at the moment the innovative source delivers heat. It represents the isolated enhancement of the innovative source.
COP + backup ASHP	This percentage shows how much higher (or lower) the SCOP of a hybrid system, consisted of the innovative source and a backup ASHP, is compared to an ASHP-only system. It represents the enhancement in efficiency caused by the integration of the innovative source in a further ASHP concept. The backup ASHP will work when the innovative source cannot provide (enough) heating.

Table 18: Explanation of the five KPIs

6.2. Thermal results

Next page presents Table 19 which consist of three tables, each representing all five KPIs for all innovative sources, one table for each demand profile: pre-renovation household, renovation household and neighbourhood. The interpretation of these results can be found in the section after these tables. The greener a cell is coloured, the better the result. The whiter a cell is coloured, the worse its result. One particular sizing is selected for the sources that come in different sizes, such as the cooling systems of food chains and datacentres or the areas of heat recovery panels in underground structures and the area of solar thermal energy. This uniform sizing methodology facilitates direct comparison of the results between one household and a neighbourhood.

Pre-renovation scenario for one household

	Attics - Sint-Michiels church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Profile match	0,3%	0,1%	0,0%	95,7%	93,3%	78,5%	63,1%	46,6%
Absolute match	479,0%	133,5%	13,4%	3685,3%	2307,8%	2780,2%	235,3%	1385,7%
Source match	0,1%	0,1%	0,0%	2,6%	4,0%	2,8%	26,8%	3,4%
COP enhancement	44,51%	36,38%	-	217,77%	229,33%	72,30%	32,09%	97,11%
COP + backup LWP	0,36%	0,02%	0,00%	217,34%	228,55%	66,64%	24,57%	53,96%

Renovation scenario for one household

	Attics - Sint-Michiels church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Profile match	1,0%	0,5%	0,1%	100,0%	100,0%	74,6%	100,0%	55,0%
Absolute match	853,7%	237,9%	23,8%	6567,9%	4112,9%	4954,9%	419,4%	2469,7%
Source match	0,1%	0,2%	0,6%	1,5%	2,4%	1,5%	23,8%	2,2%
COP enhancement	36,09%	85,84%	57,33%	211,12%	223,81%	73,04%	29,93%	97,53%
COP + backup LWP	1,09%	0,74%	0,20%	211,12%	223,81%	65,81%	29,89%	56,97%

Neighbourhood level

	Attics - Sint-Michiels church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Profile match	3,6%	1,2%	0,2%	52,2%	34,6%	39,9%	4,4%	17,3%
Absolute match	11,5%	3,2%	0,3%	88,6%	55,5%	66,8%	5,7%	33,3%
Source match	31,4%	38,5%	65,9%	58,9%	62,4%	59,8%	78,0%	52,0%
COP enhancement	1,12%	20,44%	26,97%	146,69%	160,95%	60,40%	15,55%	108,24%
COP + backup LWP	-1,45%	2,13%	1,25%	103,97%	92,36%	34,85%	0,31%	44,24%

Table 19: The summarised thermal results for all innovative sources for the different building/neighbourhood scales

6.2.1. Interpretation

Pre - renovation for single household

Conclusions:

- Very large absolute match values for several sources (food chains, datacentres, underground parking ventilation & panels and thermal cycling lanes), meaning these sources can produce much more heat than a single prerenovation household needs if their output could be stored or exported.

- Profile match is very different: food chains and datacentres have very high-profile matches (~96% and 93%), i.e., their output timing already aligns well with the household demand. Underground parking ventilation (78.5%), panels (63.1%) and thermal cycling (46.6%) are also substantial. Small / scattered sources (attics, fitness, meeting room) show negligible profile matches. This match would differ if DHW would be included in the profiles and not be supplied via local electrical systems.

- Source match is low for most large absolute producers. By contrast, underground parking panels give higher source match percentages, reflecting a closer intrinsic fit relative to their scale.

- COP enhancement is very large for Food chains and Datacentres (>200%), indicating big instantaneous efficiency gains compared with an ASHP when delivering heat. Underground parking and thermal cycling also show positive COP gains. Some small sources show moderate improvements.

- COP + backup shows nearly identical large gains for the biggest sources (food chains, datacentres) – meaning hybridising them with an ASHP yields very large seasonal efficiency benefits for a single pre-renovation house.

Take-aways:

- Many sources massively oversupply compared to one household, implying load sharing or export to neighbours is required to use the surplus.

- Small/distributed sources (attics, fitness spaces) are marginal at this scale without aggregation or very large arrays.

Renovation scenario – single household

Conclusions:

- Profile matches increase for several sources after renovation: food chains, datacentres and underground parking panels reach 100% profile match (their output aligns with the much-reduced household demand). Thermal cycling increases but remains moderate or small.

- Absolute match values remain very large for the big sources (food chains, datacentres, parking), even more so because household demand decreased.

- COP enhancement remains strong for food chains and datacentres and for others to varying degrees.

Take-aways:

- Renovation (lower heat demand) makes it even easier for large point sources to fully cover household needs in real time – profile match = 100% for several sources. That strengthens the case for direct coupling or simple hybrids rather than relying solely on ASHPs.

- However, the mismatch between very large production capacity and small post-renovation demand increases the need for storage, aggregation, or supply to multiple dwellings.

- When improving building envelope thermal insulation, you can heat the building with lower temperatures using the same radiators. Since many residual/renewable sources provide only limited temperatures, it makes integrating these sources to lower temperature heating systems more efficient

Neighbourhood scale

Conclusions:

- Profile match values drop compared to single household results for the largest producers (food chains 52.2%, datacentres 34.6%, underground parking 39.9%) but remain meaningful. Small sources remain negligible for providing direct realtime share.

- Absolute match at neighbourhood scale is much smaller (e.g., food chains 88.6%, datacentres 55.5%, parking 66.8%) – because demand aggregated over a neighbourhood is larger and so the same source covers a smaller share overall.

- Source match is substantially higher for nearly all sources (many ~50–80%), meaning the temporal pattern of these sources is genuinely better aligned with neighbourhood demand once scale is increased: the fraction of produced energy that can be used without extreme storage is much higher.

- COP enhancement is still positive for the main heat sources though smaller than at single-household scale in some cases. COP + backup ASHP is mixed: large positive gains for some (food chains, datacentres: 104% and 92%), but small or even slightly negative impacts for others.

Take-aways:

- At neighbourhood scale the main advantage is better utilisation of produced heat without huge relative oversupply: absolute match numbers are closer to realistic values and source match is high, showing a real temporal fit.

- Some hybrid configurations (innovative source + backup ASHP) still yield large seasonal gains (notably food chains and datacentres), but for some small/low-temperature or highly intermittent sources the hybrid can give little or no seasonal improvement.

- Aggregation at neighbourhood level materially improves the usefulness of many sources because it reduces the relative oversupply issue and increases the fraction of production that maps onto demand. Neighbourhood integration and distribution networks become attractive for these sources.

6.2.2. Overall comparison and recommendations

- Food chains (100 kW) and Datacentres (50 kW) are consistently the strongest candidates: high profile match, huge available energy and very large COP improvements both instantaneously and in hybrid seasonal performance.

- Underground parking (ventilation and especially panels) and thermal cycling lanes are also promising, particularly when aggregated or used as part of a hybrid system.

- Small/distributed sources (attics, fitness, meeting room) generally provide negligible direct contribution to a single household and limited neighbourhood contribution unless aggregated at scale.

Storage and aggregation are essential: many promising sources massively oversupply a single dwelling. Thermal storage, neighbourhood networks, or power-to-heat/cold solutions will be required to make their energy usable. Single large point sources can serve single renovated houses easily, but that creates a scale mismatch; neighbourhood integration usually gives a more balanced, resilient solution.

6.3. Financial results

Next page presents Table 20 which consists of three tables, each representing the electrical consumption and the energy cost savings for each innovative source, one table for each demand profile: pre-renovation household, renovation household and neighbourhood. The energy and cost savings were compared to a system that consist of only air-source heat pumps; so, if previous table presented an enhanced COP for the innovative source, the system will save electricity and costs. An electricity price of 0,45 €/kWh was used. The interpretation of these results can be found in the section after these tables. The greener a cell is coloured, the better the result. The whiter a cell is coloured, the worse its result.

Pre- renovation scenario for one household

	Attics - Sint-Michiels church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Annual electrical consumption	7.346	7.350	7.351	2.345	2.331	4.520	5.948	5.636
EC reduction	-0,07%	-0,01%	0,00%	-68,10%	-68,28%	-38,51%	-19,09%	-23,33%
Electricity cost	€ 3.306	€ 3.307	€ 3.308	€ 1.055	€ 1.049	€ 2.034	€ 2.676	€ 2.536
Cost savings	-€ 2	€ 0	€ 0	-€ 2.253	-€ 2.259	-€ 1.274	-€ 631	-€ 772

Renovation scenario for one household

	Attics - Sint-Michiels church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Annual electrical consumption	4.138	4.137	4.145	1.266	1.214	2.329	3.025	3.049
EC reduction	-0,22%	-0,24%	-0,03%	-69,47%	-70,73%	-43,84%	-27,06%	-26,47%
Electricity cost	€ 1.862	€ 1.862	€ 1.865	€ 570	€ 546	€ 1.048	€ 1.361	€ 1.372
Cost savings	-€ 4	-€ 4	-€ 1	-€ 1.296	-€ 1.320	-€ 818	-€ 505	-€ 494

Neighbourhood level

	Attics - Sint-Michiels church	Densely populated - fitness	Densely populated - meeting room	Food chains - 100kW	Datacentres - 50kW	Underground parking - ventilation air	Underground parking - 100 panels	Thermal cycling lanes - 1000m²
Annual electrical consumption	288.529	288.167	288.720	148.710	176.255	225.088	285.043	261.299
EC reduction	-0,11%	-0,23%	-0,04%	-48,52%	-38,98%	-22,07%	-1,32%	-9,54%
Electricity cost	€ 129.838	€ 129.675	€ 129.924	€ 66.920	€ 79.315	€ 101.290	€ 128.270	€ 117.584
Cost savings	-€ 141	-€ 304	-€ 55	-€ 63.060	-€ 50.665	-€ 28.689	-€ 1.710	-€ 12.395

Table 20: The summarised economical results for all innovative sources for the different building/neighbourhood scales

6.3.1. Interpretation

Pre - renovation for single household

- The largest electricity reductions (about 38–68 %) occur for the large, steady waste-heat sources: food chains (≈68 %), datacentres (≈68 %), and underground parking – ventilation air (≈39 %). Thermal cycling lanes and the panel underground parking give moderate reductions (≈19–23 %). Small or negligible changes occur for small, intermittent sources (attics, fitness, meeting room), with reductions near zero, meaning these add almost no net electrical savings at household scale.

- Cost savings mirror the electricity consumption eductions. The biggest absolute savings per household are for food chains and datacentres (≈€2.250 each pre-renovation), followed by underground ventilation and thermal lanes. Small sources yield negligible or zero savings.

Renovation scenario – single household

- Renovation reduces demand and thus absolute savings possible from any source, but the relative value of abundant, well-matched sources remains high.

- Percentage reductions are similar or slightly larger for the large sources after renovation: food chains and datacentres show ~69–71 % reductions, underground parking ventilation ~44 %, thermal cycling lanes and panels smaller but still relevant (~27–43 %). Small/mismatched sources remain negligible.

- Absolute cost savings per household are smaller than pre-renovation (because the energy need is lower), but relative reductions remain large for the major continuous sources. Small sources again yield only small or no savings.

Neighbourhood scale

- At neighbourhood scale the relative reductions for food chains and datacentres remain substantial (≈39–49 %). Underground parking ventilation and thermal cycling lanes give moderate neighbourhood reductions (≈9–22 %). The small sources (attics, fitness, meeting room) produce only minor neighbourhood-level reductions (fractions of a percent).

- Cost savings at neighbourhood scale are large in absolute terms for food chains and datacentres (tens of thousands of euros saved), moderate for underground ventilation and thermal cycling lanes, and negligible for the smallest sources.

- Aggregation at neighbourhood level improves the usefulness of moderately sized sources but does not overcome fundamental mismatch for very small or highly intermittent sources. Large, continuous waste-heat producers still yield the largest absolute and relative electricity and cost savings when integrated into hybrid systems at district scale

6.3.2. Overall comparison and recommendations

Food chains and datacentres are clearly the most effective innovations in terms of electricity reduction and cost savings at household and neighbourhood scale due to their continuous availability. Underground parking ventilation and thermal cycling lanes provide meaningful, but smaller, benefits. The underground parking panels and small, intermittent sources (attics, fitness, meeting room) produce minimal household-level benefit. Renovation reduces absolute savings, but it does not change the ranking of source effectiveness.

Many sources show very high absolute production potential (absolute match >>100 %), meaning they could supply far more heat than a single household needs. Where profile match is low but absolute match is high, storage, temporal aggregation (neighbourhood networks), or load shifting is required to capture the potential. Conversely, sources with good profile match but limited absolute production only partially displace ASHP electricity.

Cost savings follow energy savings. For a homeowner, only the well-matched, high intensity sources produce meaningful reductions in electricity bills. For municipalities or district planners, integrating large waste heat sources into neighbourhood/district supply yields large aggregate savings.

Advise based on these results

Prioritize integration of continuous waste-heat sources (food chains, datacentres, large ventilation systems) into hybrid ASHP systems at household and neighbourhood scale for the largest energy and cost benefit.

Where sources produce large excess heat relative to single-household demand (absolute match >>100 %), plan for storage, heat networks, or sector coupling to exploit surplus rather than curtailing it.

Small/intermittent sources are not valuable on their own for direct household electricity reduction. After envelope renovation, benefits shrink in absolute euro terms, so economic feasibility should be reassessed post-retrofit – but large sources remain beneficial. However, when the space heating demand decreases, the impact of DHW increases, arguing that the DHW provision should be integrated and not being supplied by decentral electrical systems.

7. Discussion

7.1. Calculations

For the continuous heat sources, calculations have been performed for various cooling capacities that could be present in buildings requiring constant cooling. Multiple parameters were assumed, as these are often case-specific, to facilitate an initial assessment of potential gains associated with heat recovery within a smaller thermal network.

Climate data from 2024 was utilised in the calculations to determine the Energy Efficiency Ratio (EER) on an hourly basis, based on the outdoor temperature from the neighbourhood case study of Ghent. This approach implies that in colder climates or years with lower average temperatures, higher EER values would be achieved for the cooling systems.

Regarding the calculation of the EER on an hourly basis, a default value of 0.05 was used for the EER slope, along with manufacturer data corresponding to tested conditions. Additional measurements or simulations are recommended to validate this default value. In specific cases, the calculation should be performed using manufacturer data relevant to the existing cooling system, incorporating local control strategies. However, such details were not included in these simplified computations.

When estimating the theoretically recoverable heat, system losses were considered as not all heat can be effectively recovered. Follow-up measurements are necessary to verify the assumed 85% efficiency level.

One of the critical factors influencing these calculations is the condenser outlet temperature set at 35°C, which was used for these calculations. This temperature impacts the operating regime post-heat exchanger because the outlet temperature cannot physically exceed this value. Variations in this temperature in specific scenarios will directly affect the coefficient of performance (COP) of the heat pump powered by the recovered heat.

The distribution systems are assumed to run at a 45°C supply temperature, enabling low-temperature operation; requiring higher temperatures reduces COP and may necessitate specialized high-temperature heat pumps (e.g., propane-based). Lower supply temperatures increase COP for both system and reference air-to-water heat pumps. With heat recovery condenser temperatures around 35°C a heat pump is still needed to reach supply temperature, whereas at higher condenser temperatures direct heat supply to the building may be possible.

For each cooling capacity, the required mass flow rate has been determined to achieve a delta T of 5°C in the thermal network. Table 21 indicates the diameter of pipes needed at a design velocity of 1.0 m/s.

Cooling capacity (kW)	Mass flow (kg/s)	Calculated diameter (mm)	Corresponded DN	Corrected velocity (m/s)
50	2,39	55,2	DN20	0,76
60	2,87	60,4	DN25	0,97
75	3,58	67,5	DN40	0,76
100	4,78	78,0	DN65	0,72
150	7,17	95,5	DN125	0,97

Table 21: Pipe diameters at a design velocity of 1.0 m/s, for different cooling capacities

The size of the pipes also reflects the feasible working dimensions; larger pipes are unlikely to be suitable for individual residential applications, as they are incompatible with residential heat pumps and would require branching. Depending on a specific situation, a design choice for a particular mass flow rate must be made, which may result in not all heat being utilized.

If insufficient heat is absorbed, the return temperature will be higher, leading to less heat being recovered from the cooling system in subsequent cycles.

To reduce pump energy, the mass flow rate will not be constant. Dynamic simulations can further demonstrate these effects on temperatures, including the return temperature, which is not constant as assumed in these static calculations.

In the calculations of recovering solar thermal energy, no impact form shadows was assumed which is of course an issue in urban local neighbourhoods. It is however difficult to assume a general reduction on the thermal energy as the shadowing is case-specific and could vary significantly depending on the case.

7.2. Impact of local climate

The findings predominantly pertain to the case study neighbourhood in Ghent, Belgium, as data were collected through a dedicated measurement campaign. It is important to note that these results are context-specific and may vary under different climatic conditions. For innovative energy sources that are less sensitive to local climate fluctuations, the relative advantages are likely to be more pronounced outside the mild climate prevalent in Ghent. Conversely, efficiencies tend to decline in colder climates, where lower outdoor temperatures adversely affect performance. In warmer climates, greater heat recovery potential may be achievable, potentially resulting in an improved alignment with energy demand profiles—though it should be acknowledged that similar effects can also be observed in traditional heat pump systems that utilize outdoor air as a heat source.

7.3. Demand profiles

The results are given for the demand profiles as described in chapter 6.1 but in cases where the envelope is more thoroughly renovated, the heating demand will be lowered which could benefit certain innovative sources. The impact of storage systems should be researched as well for sources that are not feasible due to a mismatch of profiles.

As the DHW in the current scenarios is provided by electric boilers, the DHW is not included in the current demand profiles comparisons. It is important to note that when DHW would also be provided by a central heating system, it will become more essential when the envelope will be continuously renovated, as the share of room heating becomes smaller, but the demand of DHW remains the same.

7.4. Restrictions

During a work package meeting with experts within the HeriTACE project, it became clear that these resources often remain innovative due to various restrictions that complicate practical feasibility, technical feasibility, or financial feasibility.

7.4.1. Practical feasibility

There is significant waste heat available in public buildings. To appropriate this waste heat for individual households or smaller communities, a permit shall be required to install a heat recovery system. This process can lead to lengthy procedures that may delay renovations.

Recovering heat sources is simpler for private buildings. However, the owner must be convinced to participate in the small-scale heat recovery initiative.

Additionally, a thermal network must be provided. The placement of the heat source in relation to its utilization can complicate installation, especially if it must run through public roads due to permit applications or limited space from existing piping routes.

Finally, there is the issue that the technologies must not impact the visual aesthetics of the historical city centre. Technologies with a visual impact, like integrated solar panels, may face permitting challenges.

7.4.2. Technical feasibility

In the use of small thermal heating networks to transport heat from the innovative source to the location where the heat can be used, no account has yet been taken of heat losses from the pipes and pump energy, which will affect the profitability of the system. This has not yet been included since it depends on various factors that are situation-specific: such as:

- Length of the route
- Available space, influencing pipe thickness
- Flow speed

It will always be more advantageous to keep the route as short as possible to limit pipe losses and to keep pump energy to a minimum.

However, for each situation, it will need to be calculated what the effect is on the final technical feasibility of the systems.

7.4.3. Financial feasibility

Innovative sources are often underutilized on a smaller scale due to necessary investments in heat exchangers, piping, and pumps. The temperatures of waste heat sources frequently fall short for direct use in distribution systems, requiring the installation of additional heat pumps to raise temperatures. This increases investment costs compared to individual production systems.

If multiple households can share these costs, the system becomes more appealing; however, this must be evaluated on a case-by-case basis.

Additionally, financial profits may need to be shared with the heat source owner. The owner could opt to sell waste heat to allow the installation of a heat recovery system, resulting in a longer payback period for the waste heat user.

7.5. Impact on the CO_2-emissions

In this study is only focussed on the energy consumption and reduction using innovative sources. A reduction in energy consumption generally leads to lower CO_2 emissions However, it should be noted that the impact of the embodied CO_2 in the additional materials that are needed for the thermal heating network, heat exchangers… may not be forgotten. For example, recovering solar thermal energy in open spaces will require a lot of plastic pipes. More studies are necessary to ensure that the embodied CO_2 does not outweigh the potential CO_2 savings gained from reducing energy use with residual heat sources.

8. Conclusion

This deliverable has explored the feasibility of integrating heat recovery from unharvested local sources within heritage environments, particularly focusing on urban historical neighbourhoods. Through a systematic process—starting from a broad longlist of innovative energy concepts and narrowing to a shortlist based on proximity, energy potential, technical feasibility, and restrictions—the study provides a robust assessment of how various unconventional waste heat sources and renewable technologies fit the unique constraints and opportunities of heritage areas.

Key Findings

The analysis identifies continuous waste heat sources—such as food chains (supermarkets), micro and small datacentres, and underground transport facilities such as car parking and metro's tunnels—as the most promising candidates. These sources typically offer high absolute energy potential, well-matched supply profiles, and substantial seasonal COP improvements.

Thermal cycling lanes and solar thermal collectors integrated into urban surfaces also present notable opportunities, albeit with greater technical and regulatory challenges.

Concepts like attic heat recovery, densely populated spaces, and vibration energy harvesting are feasible in certain neighbourhoods but offer only modest supply and savings at household or neighbourhood scale unless large-scale aggregation is realized. Rainwater buffering and gravitational battery storage are less suited to heritage environments due to scalability and proximity limitations.

Many sources, especially large point producers, can supply far more heat than individual households require (although not directly as the temperature regimes are too low), underlining the need for heat storage, aggregation, and neighbourhood-level thermal networks to fully realize their potential and avoid energy curtailment. Since these sources are often large-scale, neighbourhood solutions are preferred over individual households. Integrating major continuous sources into hybrid heating systems yields significant reductions in electricity consumption and heating costs, especially at a neighbourhood scale.

The results are in line with what could be expected from literature findings and real-case scenarios. Large continuous sources are already used in several cases when district heating is available. This study supports the current practice and shows the feasibility of recovering heat in smaller thermal heating networks. No innovative sources result in a significant higher efficiency for smaller scaled thermal heating networks compared to larger scaled district heating network. However, if no district heating network is available, smaller scaled thermal heating network appears to be a trustworthy alternative.

Critical Considerations

Despite their technical promise, innovative heat recovery concepts face several practical hurdles. Implementation challenges include permitting processes in public and heritage buildings, owner participation, visual and infrastructural constraints due to conservation rules, and the complexity of installing thermal networks in dense urban fabrics.

Investment and payback—while large sources can be economically attractive when costs are shared and infrastructure serves multiple dwellings, smaller or intermittent sources often fail to deliver significant savings at household scale.

Outlook

The transition to neighbourhood-scale low-carbon heating in heritage cities is highly feasible when leveraging continuous, high-yield waste heat sources and integrating them with established and storage technologies. The findings set a clear direction for municipalities, building owners, and energy planners: exploit locally available, steady waste heat and renewable sources at scale:

- food chains (supermarkets),
- micro and small datacentres,
- and underground transport facilities;

coordinate interventions across time and space; and address regulatory, aesthetic, technical, and financial challenges hand-in-hand to realize optimal comfort and energy performance in heritage built environments.

Nevertheless, the implementation in practice and economic feasibility are greatly dependent on specific circumstances, including factors such as the accessibility of these sources, along with the distance to the neighbourhoods targeted. Additional research is necessary to determine how the specific conditions will influence outcomes and to compare the investment costs with those of conventional systems. This additional research can be included within the HeriTACE project by integrating these sources into simulations that reflect actual conditions in the case-study neighbourhoods.

9. References

About Amazon Team. (2020, december 14). *Local community buildings in Ireland to be heated by Amazon data centre*. Retrieved from aboutamazon: https://www.aboutamazon.eu/news/amazon-web-services/local-community-buildings-in-ireland-to-be-heated-by-amazon-data-centre

Alley, A. (2020, july 9). *Facebook plugs its Danish data center into Odense district heating system*. Retrieved from datacenterdynamics: https://www.datacenterdynamics.com/en/news/facebook-begins-installing-district-heating-system-odense-data-center-denmark/#:~:text=Facebook%20has%20announced%20that%20its,is%20Denmark%27s%20third%2Dlargest%20city

Amaya V. Novo, J. R.-F.-H. (2010). Review of seasonal heat storage in large basins: Water tanks and gravel–water pits. *Applied Energy*, 370-397.

Anna Ladenberger, N. A. (2018). *Identification and quantification of secondary CRM resources in Europe.* European Comission.

Belgian waste to energy. (2016). *Wat is waste-to-energy?* Retrieved from bw2e: https://bw2e.be/wat-is-waste-to-energy

Belgian waste to energy. (2020). *Hoeveel energie produceert de waste-to-energy sector in België?* Retrieved from bw2e: https://bw2e.be/veelgestelde-vragen-faq-2

Buildwise. (n.d.). *Moet een gesloten parking geventileerd worden?* Retrieved from Buildwise.be: https://www.buildwise.be/nl/help-center/faq/ventilatie-van-gesloten-parkings/#:~:text=Het%20ventilatietype%20en%20de%20ventilatiewaarde,0%2C2%20%25%20van%20de%20vloeroppervlakte

CELSIUS. (2017). *Progress and achievements on each demonstrator and analysis of causes for deviation.* European Union's Seventh Framework Programme for research, technological development and demonstration. Retrieved from https://celsiuscity.eu/files/wp-content/uploads/2020/02/126-d4.3_progress_and_achievements_20170430.pdf

celsiuscity. (2020, january 14). *Open District Heating in Stockholm, Sweden*. Retrieved from celsiuscity: https://celsiuscity.eu/open-district-heating-in-stockholm-sweden/

Chaturvedi, D., Yadav, S., Srivastava, T., & Kumari, T. (2020). Electricity storage system: A Gravity Battery. *Fourth World Conference on Smart Trends in Systems, Security and Sustainability (WorldS4)*.

circulair, V. (2022). *Verbrand, meeverbrand of gestort afval*. Retrieved from cemonitor: https://cemonitor.be/indicator/circulariteit/uitstroom/verbrand-meeverbrand-of-gestort-afval/

Commission, E. (2023). Advancing district heating & cooling solutions and uptake in European cities : overview of support activities and projects of the European Commission on district heating & cooling. *Publications Office of the European Union*, 280.

Commission, E. (2025, 10 10). *Photovoltaic geographical information system*. Retrieved from re.jrc.ec.europa.eu: https://re.jrc.ec.europa.eu/pvg_tools/en/

Cyclifier. (2004, 01 01). *Asphalt collector: using paved surfaces to capture solar energy*. Retrieved from cyclifier.org: https://www.cyclifier.org/project/asphalt-collector/

Danfoss, M. R. (2015, July 7). *Local residents stay warm thanks to supermarket's cooling system*. Retrieved from Danfoss: https://www.danfoss.com/en-gb/service-and-support/case-stories/dcs/local-residents-stay-warm-thanks-to-supermarket-s-cooling-system/

Elina Mäki, E. T. (2015). *The role and opportunities for solar energy in Finland and Europe.* JULKAISIJA.

Enerdrape. (2025). *Untapped Underground Energy*. Retrieved from enerdrape: https://enerdrape.com/en/

Energy Floors. (2025). *The moves of the public as a source of energy*. Retrieved from energy-floors: https://energy-floors.com/products/kinetic-dancefloor/

Fjärrvärme, Ö. (2015). *Profitable recovery with Open District Heating.* Fortum.

fluvius. (2025, 03 27). *Capaciteitswijzer*. Retrieved from opendata.fluvius: https://opendata.fluvius.be/pages/map_perceel/

Gareth Davies, N. B.-H. (2017). *Metropolitan Integrated Cooling and.* London: London South Bank University.

GEP. (n.d.). *Energie uit regenwater bij een woning*. Retrieved from gepwater: https://gepwater.com/energie-uit-regenwater/

Howard, J. (2015, may 13). *World's First 'Solar Road' Is Generating Even More Power Than Expected*. Retrieved from huffpost: https://www.huffpost.com/entry/solar-road-power_n_7275278

Hussein Janna, M. D.-K.-A. (2021). Energy Content Estimation of Municipal Solid Waste by Physical Composition in Al-Diwaniyah City, Iraq . *Journal of Ecological Engineering*, 11-19.

IES VE. (2025). *IES VE*. Retrieved from IES VE: https://www.iesve.com/

Julia Almebäck, R. M. (2022). *Heat Export from Supermarkets' Refrigeration Systems: Field Measurements and a Techno-economic Analysis.* Stockholm, Sweden: KTH Royal Institute of Technology: School of Industrial Engineering and Management.

Keane, K. (2021, april 21). *Gravitricity battery generates first power at Edinburgh site*. Retrieved from BBC: https://www.bbc.com/news/uk-scotland-56819798

Leefmilieu Brussels. (2022, March 22). *Overdekte en ondergrondse parkings*. Retrieved from leefmilieu.Brussels: https://leefmilieu.brussels/pro/regelgeving-en-inspectie/verplichtingen-en-vergunningen/overdekte-en-ondergrondse-parkings

Lepinoy, K. (2023-2024). *Erfgoedgebouwen met zelfvoorzienend thermisch energiesysteem.* Leuven: KU Leuven - faculty of engineering science.

Ltd, B. E. (2025). *Transformer Cooling and Methods of Cooling*. Retrieved from bowerselec: https://www.bowerselec.co.uk/insights/transformer-cooling-and-methods-of-cooling/

McConnell, I. (2024, february 5). *Gravitricity to demonstrate energy storage tech in deep mine*. Retrieved from The Herald: https://www.heraldscotland.com/news/24094926.gravitricity-demonstrate-energy-storage-tech-deep-mine/

Mohammad Farhan, A. G. (2024). Innovative approaches to optimize vibration energy harvesting (VEH): A comprehensive review. *Energy Reports*, 5194-5219.

Murphy, A. R. (2021). *Techno-economic study of an energy sharing network comprised of a data centre and MURBs for cold climate.* Toronto: Toronto Metropolitan University.

Niklas Söderholm, T. N. (2025). Demand response potential of a grocery store refrigeration and heat pump system for heat recovery by using real time electricity pricing. *Energy and Buildings*.

NMBS. (2024, oktober). *Cijfers opgestapte reizigers*. Retrieved from belgiantrain: https://www.belgiantrain.be/nl/about-sncb/enterprise/publications/travellers-counts

Onset Computer Corporation. (n.d.). *HOBO U12 Temp/RH.* Retrieved from HOBO U12 Temp/RH Data Logger (Part #U12-011): https://www.onsetcomp.com/sites/default/files/resources-documents/13127-B%20MAN-U12011.pdf?srsltid=AfmBOorKahj2VoLAZO8mIyH3aDipSOqZDL3Zeu0P22vHbZXcljPWHys6

OpenModelica. (2025). *OpenModelica*. Retrieved from OpenModelica: https://openmodelica.org/

Panasonic. (2022). *Catalogus ECOi-W Chiller 2022/2023.* Retrieved from panasonicproclub: https://www.panasonicproclub.com/uploads/NL/catalogues/Catalogus%20R32%20Chiller%20DIG.pdf

Rania Rushdy Moussa, W. S. (2022). Energy generation in public buildings using piezoelectric flooring tiles; A case study of a metro station. *Sustainable Cities and Society*.

ReUseHeat Project. (2017, december 22). *Heat recovery from the London Underground in Islington, UK*. Retrieved from Euroheat & Power: https://www.euroheat.org/dhc/knowledge-hub/heat-recovery-from-the-london-underground-in-islington-uk

Royal Meteorological Institute of Belgium. (n.d.). Retrieved from https://opendata.meteo.be/

Rudzka, M. (2019, september). *ReUseHeat – Excess heat recovery from data centre in Braunschweig, Germany.* Retrieved from districtenergyaward: https://www.districtenergyaward.org/wp-content/uploads/2019/09/19GDECA-Desc-ReUseHeat-BraunschweigDE.pdf

SolaRoad. (2014, october 21). *Press release: SolaRoad opens the first road in the world that converts sunlight into electricity is ready for use.* Retrieved from solaroad: https://www.solaroad.nl/wp-content/uploads/2013/06/PressReleaseSolaRoadOpened_21Oct.pdf

SolaRoad. (2025). *Product development*. Retrieved from solaroad: https://www.solaroad.nl/products/

STATBEL. (2025, september 23). *Gemeentelijk afval per inwoner is met 2,4% gestegen*. Retrieved from statbel.fgov: https://statbel.fgov.be/nl/themas/leefmilieu/afval-en-vervuiling/gemeentelijk-afval

Vault, E. (2024). *g vault gravity energy storage*. Retrieved from energyvault: https://www.energyvault.com/products/g-vault-gravity-energy-storage

Xiaolei Yuan, Y. L. (2023). Waste heat recoveries in data centers: A review. *Renewable and Sustainable Energy Reviews*.