Report on decarbonisation design-approaches based on urban typologies

Deliverable 2.5

AUTHORS

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Published: September 2022

PROJECT INFORMATION

Project name: Decarb City Pipes 2050
Grant agreement number: 893509
Project duration: 2020-2023

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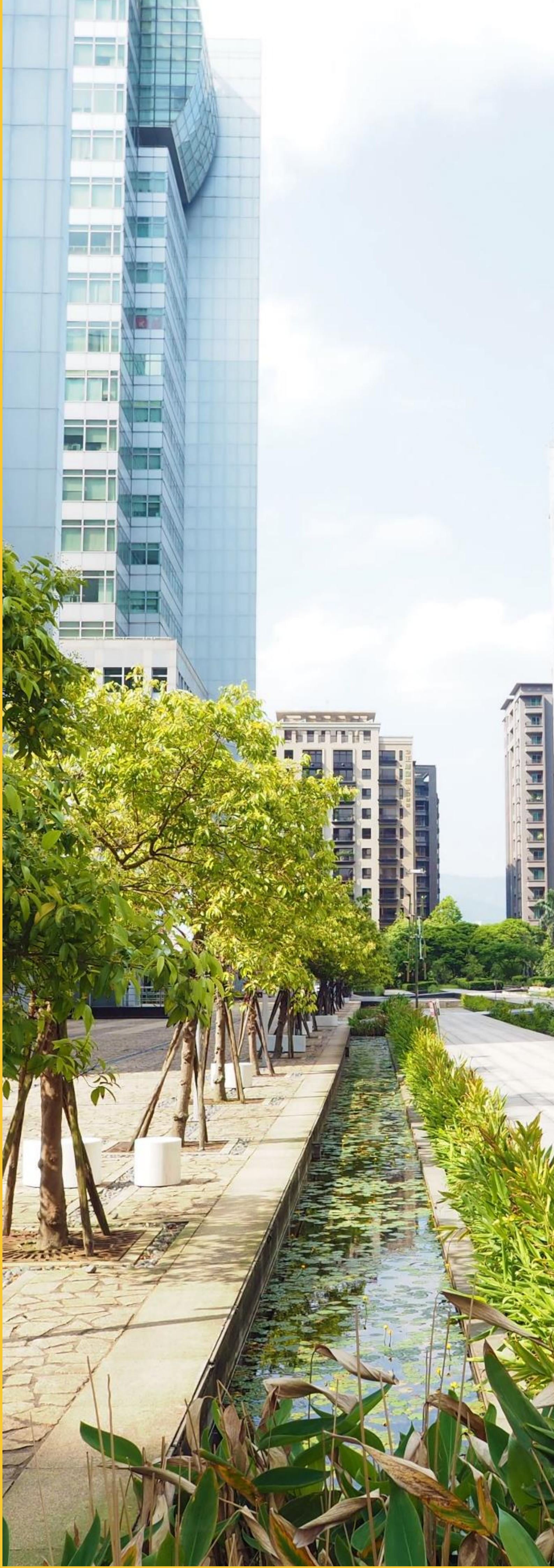

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Introduction

The underlying task for this report (deliverable) was to develop design approaches for urban « H/C landscape typologies ». These design approaches are based on a typology commonly found in European cities. Besides the newly developed typology, this report also includes existing findings from literature as well as relevant findings from the *Decarb City Pipes 2050* (hereafter abbreviated with DCP) project.
In summary, the specific objective of this deliverable is to develop and present different design approaches for an urban typology.

This report is part of Work Package 2 called "Heating and Cooling Outlook 2050" of the DCP project. Another important outcome of this work package is the cross-city synthesis of H/C outlooks presented in Deliverable 2.6 "H/C outlook 2050 in each participating city and cross-city synthesis", which builds on the structuring criteria of the typology presented in this report (see chapter "Design-approaches for a database driven typology").

It is important to note that this report is not about developing a typology based on districts or neighbourhoods in the participating cities of the DCP project and corresponding design approaches on this spatial level. A comparison at district level in each participating city is not useful because the specific decarbonisation strategies of each city are already included in the H/C mapping of Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis". Further, each participating city in the DCP project alone has access to local-level data, local site-specific know-how, and knowledge about the institutional context, necessary for a detailed city district-level analyses, which is generally a prerequisite to decarbonise their own city. Therefore, the detailed planning of decarbonisation is up to the individual city.

However, the typologies presented in this report, although being rather general in their nature, are intended to give the DCP cities as well as other cities (beyond the DCP cities) a comprehensive overview of how decarbonisation can be approached from a strategic perspective.

Before the structure of this report is explained in more detail, some explanations and definitions are presented below.

So-called ***design approaches*** for « H/C landscape typologies » include concrete measures on how to achieve the decarbonisation of a specific typology. Each design approach depends on the conditions and characteristics of the underlying typology. Hence, the design approaches correspond partly to urban typologies, but also to different decarbonisation strategies. A typology is described as « *the study of types, or a system of dividing things into types* » (Cambridge University Press 2022). In this report, each type is represented by a certain set of (structuring) criteria. Examples for *criteria* are : Building density (number of buildings per hectare), heat demand density (MWh/ha.a), construction period or type of buildings (residential, commercial,…) or available local energy sources. Each criterion can then be classified. For example, a ***classification*** of heat demand density could be: < 20 TJ/km^2 ; 20 – 50 TJ/ km^2 etc.

In the context of this deliverable, a ***typology*** is understood as follows: A combination of different structuring criteria and their underlying classification may constitute a particular type. Different design approaches for decarbonisation can be elaborated for each type.

This report starts with a brief chapter on existing typologies, including a study by the Technical University of Darmstadt and a typology elaborated for the city of Vienna. The following chapter examines and summarises the decarbonisation approaches of the cities participating in the DCP project, approaches which have been elaborated in association with earlier project deliverables and outputs: The H/C plans of Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“, which provides an overview of the underlying criteria for the development of the H/C plans. The final section introduces a developed typology based on a set of structuring criteria and underlying data from public repositories (from several other EU projects).

Existing Urban H/C typologies

In this chapter, two existing approaches of urban typologies are presented. First, a typology of energetic urban areas developed by the Technical University of Darmstadt is summarised. The second typology was developed for the city of Vienna and is intended to provide a second example of what a typology can look like and what criteria it is based upon.

A typology of energetic urban areas

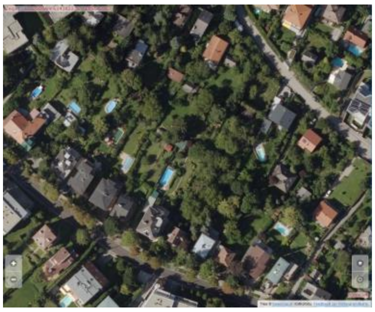
In this first part, defined profiles of urban areas and their underlying methodology from a German research project are presented (Hegger & Dettmar 2014). With these profiles a typological and energetic characterisation of urban areas can be performed. Different profiles can be understood as a typology, a typology of energetic urban areas. It is important to mention, that the approach developed by the Technical University of Darmstadt, is based on settlement types and not on individual buildings. More precisely, the urban areas are characterised by settlement-related, building-related, energy demand-related, and energy provision-related criteria. Accordingly, the urban areas that are referred to in German as *"Energetische Stadtraumtypen"* are referred to in the following as "*energetic urban areas" (EUA)*.

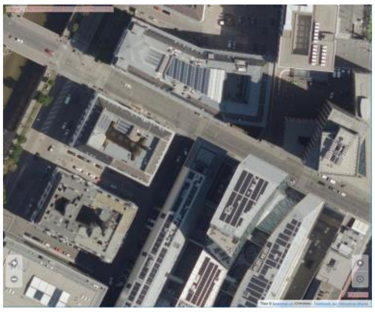
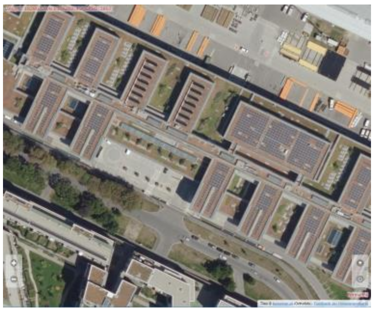
The typology consists of ten different energetic urban areas, summarised in three groups:

- Predominantly residential use
- Predominantly mixed use
- Predominantly office and commercial use

Table 1 shows the different energetic urban areas as an overview. Based on the description of the areas, samples (aerial photos) from Vienna were gathered.

TABLE 1 : PRESENTATION OF ENERGETIC URBAN AREAS IN VIENNA (ENERGETIC URBAN AREAS FROM HEGGER & DETTMAR 2014, AERIAL PHOTOS FROM WWW.BASEMAP.AT)

Group	*Energetic urban areas*	*Example aerial photos from Vienna*
Predominantly residential use	EUA1 – Small-scale, detached residential development with low to medium storeys	 www.basemap.at
Predominantly residential use	EUA2 – Terraced house development	 www.basemap.at
Predominantly residential use	EUA3 – Row development with low to medium storeys	 www.basemap.at
Predominantly residential use	EUA4 – Large-scale residential development with high storeys	 www.basemap.at

Predominantly residential use	EUA5 – Perimeter block development	 www.basemap.at
Predominantly mixed use	EUA6 – Village development	 www.basemap.at
Predominantly mixed use	EUA7 – Historical old town development	 www.basemap.at
Predominantly mixed use	EUA8 – Inner city development	 www.basemap.at
Predominantly office and commercial use	EUA9 – Development with mainly office, commercial and administrative use	 www.basemap.at

Predominantly office and commercial use	EUA10 – Commercial/industrial area	 www.basemap.at

Each of these energetic urban areas are based on a specific profile, which in turn is derived from specific criteria. The most important criteria on which the profiles are based are presented below:

Settlement related:

- Number of buildings per hectare
- Number of dwelling unites per hectare
- Number of inhabitants per hectare (Population density)
- Building density (Plot ratio)
- Type of use [%]
- Size of building block [m^2]
- Number of buildings per block
- Plot size [m^2]
- Length street front [m]
- Sealed surfaces [%]
- Open space [%]

Building related:

- Type of buildings [%]
- Number of full storeys
- Building footprint [m^2]
- Living area [m^2/ha]
- Commercial area [m^2/ha]
- Surface-area-to-volume-ratio [m^2/m^3]
- Envelope area per inhabitant [m^2/inhabitant]
- Roof area per inhabitant [m^2/inhabitant]

Energy demand related [MWh/a]**:**

- Annual space heating demand [MWh/ha.a] divided into:
  - Building periods
  - State of refurbishments
- Annual hot water demand [MWh/a]
- Annual electricity demand [MWh/a]

Energy provision related [MWh/a]**:**

- Photovoltaic [m^2/ha.a]
- Solarthermal energy [m^2/ha.a]
- Waste water [m^3/ha]
- Geothermal energy [number of drillings per hectare]
- Biomass [t/ha]

Significance for energy planning

The energetic urban areas and their underlying criteria can also be used to derive decarbonisation strategies or so called design-approaches. In the following, sample approaches are provided. A potential design-approach would be to **focus on specific renewable energy potentials** for the respective energetic urban area. Mainly office and commercial areas such as EUA9, indicate comparably high photovoltaic and solar thermal energy potentials, whereas less densly built areas, such as commercial/industrial areas, as well as sparsely built-up residential areas (e.g. EUA9, EUA10, EUA4, EUA3 and EUA1), show high potentials for heat pump applications (geothermal and wastewater heat pumps). In terms of **thermal renovation potentials**, focus should be on mixed areas with high energy demand densities (EUA5, EUA6 and EUA7) and buildings of different building periods. Less renovation potential is seen for inner city developments (EUA8), which mostly consist of new or already renovated buildings and mainly residential areas with low heat demand densities (e.g. EUA1, EUA2 and EUA3). Similarly the **focus for district heating** should be on areas with high energy demand densities and a mix of different functions (residential, commercial, etc.) to also increase full-load hours. Suitable energetic areas for this design approach would be EUA5 or EUA7 and perhaps also EUA4 and others depending on chosen design approach.

Existing typologies in Vienna

The first existing typology described in this section was developed by the City of Vienna (Magistratsabteilung 18, 2016). The developed « typology of residential areas » focuses only on residential buildings. Starting point for the evaluations were the structuring criteria building density and construction period. Spatial aggregation is based on statistical census areas as shown in Figure 1. A decision tree was defined specifically for the development of the typology. As a result, the areas are divided into the following main categories (a more detailed classification can be found at the bottom of Figure 1 in the map legend, in German):

- Single-family houses
- Single-family houses with a signficant proportion of multi-storey residential buildings
- « Gründerzeit » buildings (construction period before 1919) with a high building density and a high population density
- « Gründerzeit » buildings (construction period before 1919) and historical city areas with a high building density but a low population density
- « Gründerzeit » buildings (construction period before 1919) with low building density
- Mixed construction period, but mainly 1919-1960
- Mixed construction period, but mainly from 1961 – 1980
- Mixed construction period, but mainly from 1981 onwards

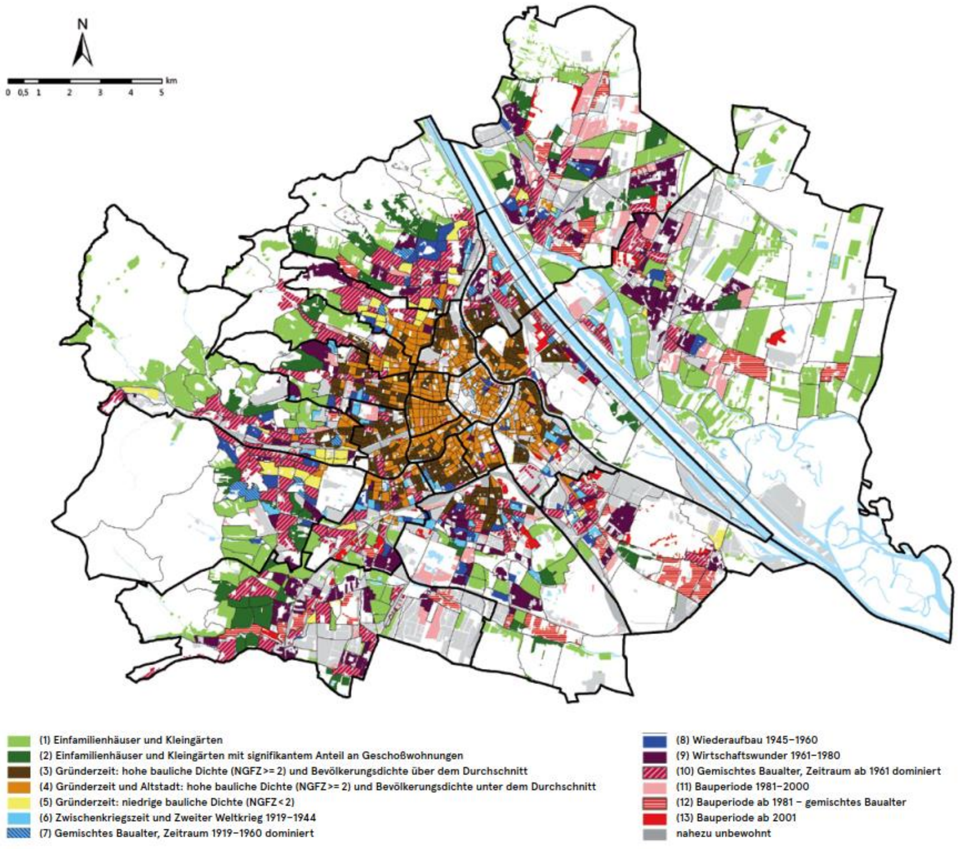


FIGURE 1 : RESIDENTIAL TYPOLOGY OF VIENNA (MAGISTRATSABTEILUNG 18, CITY OF VIENNA)

There is also a separate typology on social spaces, a so-called “social space typology” (in German “Sozialraumtypen” assembled in the so-called “Sozialraumatlas”) also developed by the City of Vienna (Magistratsabteilung 18, 2012). This typology was developed on different parameters like share of workless people / average income level / number of low class apartments et cetera. It is one element of the energy-related typologies.

The following typology was developed for the City of Vienna by the Technical University of Vienna and is summarised in (TU Wien, 2015 and in Brus et al., 2015). The goal of the project was to develop a current spatial and energy-related typology for Vienna’s building stock. In this context the focus was on the heating demand of private households with the spatial resolution of the building block. The underlying structuring criteria (also called indicators in the report) that were used for the development of the typology are:

- Reference climate (heating degree days)
- Floor area in relation to the distance to the district heating network
- Ownership structure
- Solar thermal coverage rate per inhabitant
- Solar thermal coverage rate according to heating demand
- Heating demand and energy savings potential
- Heating demand
- Sozialraumatlas (translates to social space atlas)
- Share of specific heating demand
- Gross floor area
- Solar potential
- Refurbishment potential
- Number of inhabitants
- Specific heating demand
- Gross floor area per construction period
- Proportion of residential use
- Building volume and the distribution of type of use

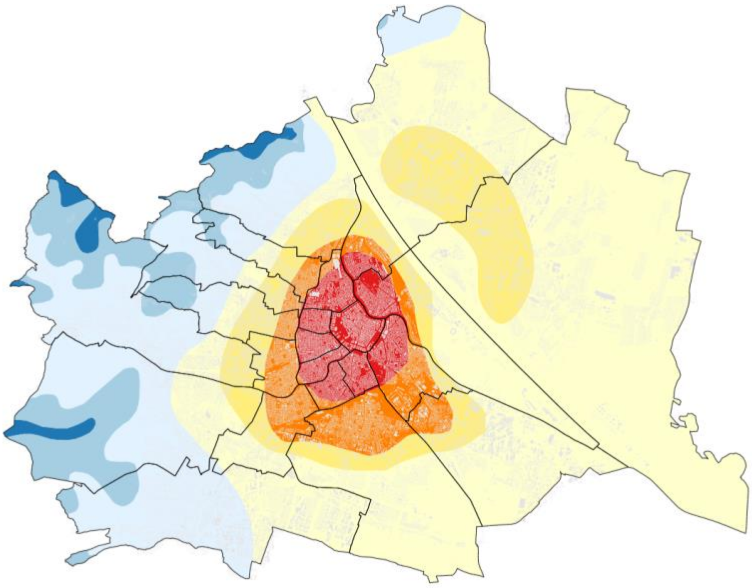


FIGURE 2 : PRESENTATION OF THE REFERENCE CLIMATE (TU WIEN 2015, 12)

Some of these criteria where summarised to 8 core elements :

- Kind of ownership (like city, federal institution or condominium)
- Heat demand
- Energy saving potentials
- Share of population without a salary (children, rentals, …)
- Distance to district heating
- Solar energy potential
- Sozialraumatlas Typ 1-3
- Sozialraumatlas Typ 3, 5, 4

For each type the relevance and the occurrence of each criteria was assessed. The results are presented in Table 2. From the multitude of characteristics, three central types could be derived for Vienna and are further explained.

TABLE 2 : OVERVIEW OF CRITERIA AND CLASSIFICATION OF VIENNESE TYPOLOGY (BRUS ET AL. 2015)

Criteria \ Type	*A*	*B1*	*B2*	*C*
Kind of ownership	-	+	+	-
Heat demand	+	o	o	+
Energy saving potentials	+	o	o	+
Share of population without a salary	+	-	-	-
Distance to district heating	+	- to o	o to +	-
Solar energy potential	+	-	-	/
Sozialraumatlas Typ 1-3	+	/	/	/
Sozialraumatlas Typ 3, 5, 4	/	+	+	/

Explanations: « + » high relevance or strong occurrence; « o » medium relevance or medium occurrence; « - « low relevance or low occurrence; « / » not considered

The first type represents areas with a high specific need for action and promising starting conditions. More specifically the first type has favourable to average conditions for a long-term supply via district heating. However, the complexity of the ownership (high share on condominiums) is a challenge to implement new measures. It is typical for very dense areas with old buildings and different uses. The second type does not have such a high energy demand but clear ownership. This type is commonly associated with social housing constructed since 1950s. It is distinguished by the distance to district heating which is an essential perimeter for the decarbonisation option. Finally the last type « C » has the most difficult situation for decarbonisation, characterised with a high energy demand, complex ownership but no option for district heating. It is an area where decentralised microgrids or renewable single solutions could be an option.

With regard to design approaches, the typology was also developed (among other things) to spatially differentiate the energy demand, to develop the need for action for energy efficiency measures or to identify certain areas with certain opportunities and obstacles towards refurbishments.

Decarbonisation approaches in the DCP cities

Cities are striving to replace fossil energy supply with promising solutions such as district heating or (individual) heat pumps. For example, the participating cities of the DCP project Munich, Rotterdam, Vienna and Winterthur already have district heating infrastructure whereas Bilbao and Dublin do not. Accordingly, the starting point for decarbonisation is different in each city. Another example is hydrogen or biogas that are not playing a major role in the ongoing decarbonisation of the heating sector of the DCP cities, especially not for space heating and hot water preparation. The individual decarbonisation strategies are not part of this report, however this chapter provides an overview of the underlying criteria of the heating and cooling plans of the participating cities in the DCP project, namely of Bilbao, Dublin, Munich, Rotterdam, Vienna and Winterthur. The plans show the cities' attempts on how to address and realise the decarbonisation of the heating systems for the existing building stock. Further details on the heating and cooling plans were elaborated in Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“.

Accordingly, the criteria used and the associated classification are summarised in tabular form below. Hence, Table 3 to Table 8 show an extract summarised from Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“. More specifically, the first column contains criteria such as the heat demand density, whereas the second column shows the corresponding classification. At the end of each table the concrete maps are shown, that represent the preferable decarbonisation approach in each city. For further details on the heating and cooling maps, please see Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“ of the DCP project.

The idea of highlighting the decarbonisation approaches (heating and cooling plans) of the participating cities in this chapter, is to get an impression and an overview of the underlying criteria of the mapping, which in turn could be useful for developing a typology. In a way, the maps are mostly based on a combination of different energy-related structuring criteria, which in turn could already reflect a typology itself. In this way, the heating and cooling plans already reflect conceivable typologies for the participating cities' districts.

Bilbao

Starting with the city of Bilbao, Table 3 shows the criteria underlying the city's decarbonisation approach. In addition to the type of heat distribution in the buildings, different types of energy sources and energy demand related criteria, the ratio between heating and cooling density is also used as an input.

TABLE 3 : CONCEIVABLE STRUCTURING CRITERIA AND DECARBONISATION APPROACH ELABORATED IN BILBAO (BASED ON DELIVERABLE 3.3 OF THE DCP PROJECT)

Criteria	*Classification*
Heat distribution within the buildings	• Central • Individual
Energy source	• Air – Water Heat Pump • Biomass • Condensing natural gas • Electricity • Gasoil • LPG • Natural gas
Heating/cooling demand per square metre (kWh/m^2)	• <15 • 15-30 • 30-45 • 45-60 • 60-90 • >90
Heat demand density (MJ/m^2)	• > 800 • 650 – 800 • 500 – 650 • 200 – 500 • < 200
Heating/cooling demand density ratio	• 0.5 – 1.5 • 1.5 – 2.5 • 2.5 – 5.0 • > 5.0
Additional information	• Potential energy sources • Available public space • Protected buildings • Public buildings • City plans (Urban planning) • Degraded areas

Decarbonisation approaches	*Classification*
Deep renovation of building blocks	Score: 1 (low potential) to 10 (high potential) 
Individual heat pumps	Score: 1 (low potential) to 10 (high potential) 
District heating and cooling networks	Score: 1 (low potential) to 10 (high potential) 

The decarbonisation approach is finally expressed in terms of renovation potential for buildings, potential for individual heat pump applications and potential for district heating and cooling networks. The potential for the implementation of the approach is expressed by a score ranging from 1 (low potential) to 10 (high potential).

Dublin

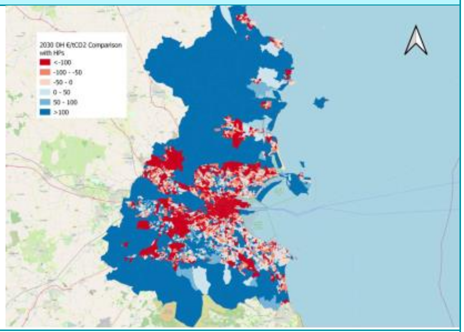
The decarbonisation approach in Dublin focuses on many criteria related to costs, such as district heating costs, heat pump costs or costs for upgrading the electricity grid. In addition, heat demand density, current heating supply technologies or available heat sources play an important role as criteria (see Table 4).

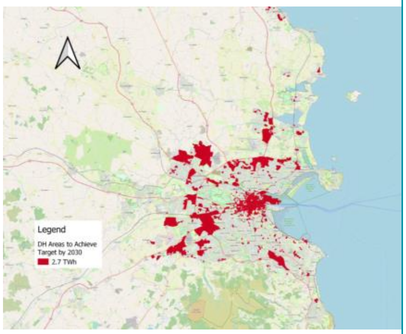
TABLE 4 : CONCEIVABLE STRUCTURING CRITERIA AND DECARBONISATION APPROACH ELABORATED IN DUBLIN (BASED ON DELIVERABLE 3.3 OF THE DCP PROJECT)

Criteria	*Classification*
Heat demand density (TJ/km^2)	• <20 (not feasible) • 20-50 (future potential) • 50-120 (feasible with supporting regulation) • 120-300 (feasible) • >300 (very feasible)
District Heating costs	For details see Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“
Heat Pump Costs	For details see Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“
Electrical Grid Upgrade Costs for Heat Pumps	For details see Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“
Emissions	For details see Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“
Current Heating technologies	For details see Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“
Available Heat sources	• Cold Storage Warehouses • Combined Heat and Power • Electrical Transformer Waste Heat • Surface Water Sources • Data Centre Waste Heat • Power Stations • Wastewater Treatment Plants • Biomass Heat Sources • Industrial Waste Heat • Area of high deep geothermal potential • Sea water heat source

<table>
<tr><th>Decarbonisation approaches</th><th>Classification</th></tr>
<tr><td>Suitability for DH (2030: DH €/tCO_2 comparison with HPs)</td><td>

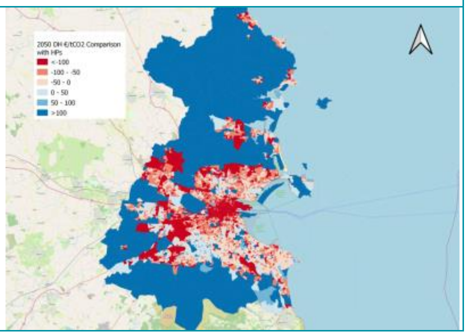
- < -100
- -100 – -50
- -50 – 0
- 0 – 50
- 50 – 100
- > 100



</td></tr>
<tr><td>Priority DH areas for achieving target by 2030</td><td>


</td></tr>
<tr><td>Suitability for DH (2050: DH €/tCO_2 comparison with HPs)</td><td>

- < -100
- -100 – -50
- -50 – 0
- 0 – 50
- 50 – 100
- > 100



</td></tr>
</table>

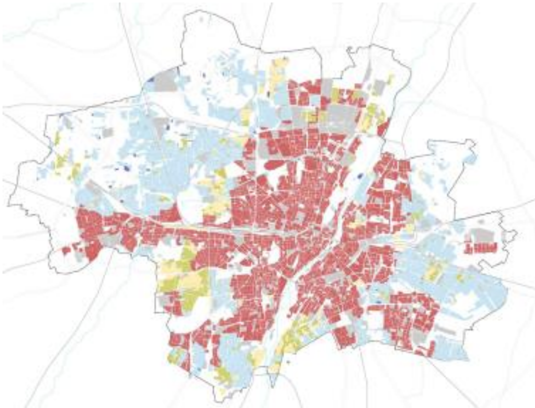
Not surprisingly, also the results of the decarbonisation approaches are related to costs. In this context, the focus is on areas mostly suited for either heat pumps (blue areas) or district heating (red areas). The final results also include the time horizon 2030 or 2050. Another important approach shows priority areas for district heating (i.e. most cost-effective) in order to achieve the set goal of 2.7 TWh of district heating by 2030.

Munich

As the second largest participating city, Munich follows a decarbonisation approach that is strongly oriented towards building and energy demand related criteria such as the residential building types, the building period, the type of heating system or the heating density. As presented in Table 5, various measures towards decarbonisation and potentials for energy saving and climate-friendly energy generation are also included in the catalogue of criteria.

TABLE 5: CONCEIVABLE STRUCTURING CRITERIA AND DECARBONISATION APPROACH ELABORATED IN MUNICH (BASED ON DELIVERABLE 3.3 OF THE DCP PROJECT)

Criteria	*Classification*
Residential building types per block	• Single family houses • Semi-detached houses and terraced houses • Apartment buildings, large apartment buildings and high-rise buildings
Heat density map	Heat demand density from high to low
Heat consumption (%)	• Residential buildings • Non-residential buildings
Building period	• <1918 • 1919 – 1948 • 1949 – 1957 • 1958 – 1968 • 1969 – 1978 • 1979 – 1983 • 1984 – 1994 • 1995 – 2001 • 2002 – 2009 • >2009
Final energy consumption (GWh/a)	• Gas • District heating • Oil
Heated buildings (amount)	• Gas • District heating • Oil
Current prevailing heat supply on building block level	• Gas • District heating • Oil
Measures	• District Heating • Retrofit + RES • Small DH • No measures
Potential for energy saving and climate-friendly energy generation	• Retrofitting • Solar heat and photovoltaic • Shallow geothermal energy • District heating (from deep geothermal energy) • Small / local district heating

Decarbonisation approaches	*Classification*
Heat supply scenarios for minimising CO_2 emissions	• District heating • Groundwater heat pumps • Groundwater heat pumps in combination with solar heat • Efficient small district heating networks • Decarbonised building-specific solutions 

The final decarbonisation approach in Munich includes heat supply scenarios for spatial units (areas) with the aim of minimising CO_2 emissions. The scenarios include areas best suited for district heating, ground water heat pumps, small district heating networks and building-specific solutions.

Rotterdam

Similar to Dublin, the design approach in Rotterdam is based on costs for district heating as well as on criteria such as the availability of alternative heat sources, heat demand related criteria, infrastructure related criteria and building related criteria (see Table 6).

TABLE 6: CONCEIVABLE STRUCTURING CRITERIA AND DECARBONISATION APPROACH ELABORATED IN ROTTERDAM (BASED ON DELIVERABLE 3.3 OF THE DCP PROJECT)

Criteria	***Classification***
Available alternative heat sources to natural gas	• Residual heat • Geothermal • Aquathermal • Biomass • Solar • Wind
Buildings	• Basic administration data • m^2 • Energy label • Surface windows/doors/roof/facade • Isolation level
Network connection	• Gas grid • Heat network • Both
Heat demand	Current use on street level
Costs district heating	For details see Deliverable 3.3
Decarbonisation approaches	***Classification***
WHAT map *How much cheaper is the preferred alternative compared to other options? (in %)*	

WHEN map *Subsequent district oriented approach to natural gas-free energy*	• Ongoing district oriented approaches • Advice to start a district oriented approach before 2025 • Advice to start a district oriented approach between 2025 and 2030 • Advice not to start a district oriented approach yet 

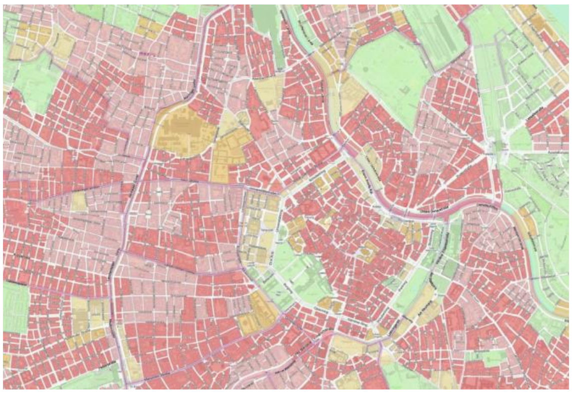
The decarbonisation approach in Rotterdam is roughly divided into the WHAT map and the WHEN map. The WHAT map shows how much cheaper the preferred alternative is compared to other options for each district. The results are expressed in %. The WHEN map includes a time schedule on when a district oriented natural gas-free approach is most advisable.

Vienna

The city of Vienna has a large number of underlying criteria that is used for its decarbonisation approach, including criteria such as the building period, the type of heat supply system, the refurbishment activities, the heat density, network density or building density. Therefore, two different typologies are used for the decarbonisation model. One focusing on the decarbonisation types depending on the type of building and the main supply as well as a distinction between refurbished or not refurbished buildings. The other system was used for an overall calculation as well as to identify the suitability for grid-based supply. Further details can be found in Table 7 and in Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis“.

TABLE 7 : CONCEIVABLE STRUCTURING CRITERIA AND DECARBONISATION APPROACH ELABORATED IN VIENNA (BASED ON DELIVERABLE 3.3 OF THE DCP PROJECT)

Criteria	*Classification*
Building period*	• < 2001 • > 2001
Type of use	• Residential • Non-residential
Gross floor area (m^2)	n/a
Heat supply system*	• Central • Decentral
Funded refurbishment activities	• Refurbished • Not refurbished
Geometry of the buildings	n/a
Heat delivery system*	• Underfloor heating • Radiators • Individual ovens
Energy carrier/fuels*	• Natural gas • Oil/coal • Electric
Thermal refurbishments*	• None • Boiler replacement • Comprehensive renovation • Partial renovation
Heating conversion*	• Air source heat pump • BIO
Renewable Energy*	• Photovoltaic • Air source heat pump
Heat density *(for the census area in m^2)*	• High: > 100 kWh/m^2 • Medium: 40 – 100 kWh/m^2 • Low: < 40 kWh/m^2
Network/pipe density	1/m in reference to a census area
Building density	% of built-up area of the census area (differentiation between “high” and “low building density”) → min. 34%

Decarbonisation approaches	***Classification***
Preferred decarbonisation solution	• District heating (Dark red areas: Central DH is broadly established; high potential to connect additional buildings to DH) • District heating – Extension (Light red areas: Central DH established but less common; potential for all remaining buildings to be connected) • Microgrid/DH – High share (Dark yellow areas: High share of existing DH, remaining areas are only suitable for central district heating to a limited extent; suitability for microgrids is high) • Microgrid/DH – low share (Light yellow areas: Low share of existing DH, remaining areas are only suitable for central district heating to a limited extent; suitability for microgrids is high) • Renewable energy single solutions (Green areas: Not suitable for grid-based heat supply; individual solutions preferred, such as shallow geothermal energy, groundwater, ambient heat, waste heat) 

*These criteria also refer to the decarbonisation types on the building level (also see D3.3)

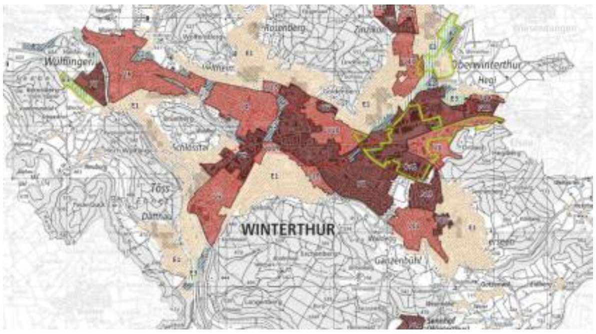
The final decarbonisation approach shows the preferred renewable supply solution for the existing building stock. The classification includes areas suitable for district heating, microgrids and areas for single renewable solutions such as geothermal energy, ambient heat or waste heat.

Winterthur

Winterthur is following a straightforward decarbonisation approach, also focusing on renewable supply solutions. As Table 8 shows, the underlying criteria are energy demand and energy potential related, including criteria for infrastructure.

Table 8: Conceivable structuring criteria and decarbonisation approach elaborated in Winterthur (based on Deliverable 3.3 of the DCP project)

Criteria	*Classification*
Heat demand density per hectare in MWh/a in 2033	• 0 – 150 • 151 – 400 • 401 – 600 • > 600
Cooling demand	• Low • Middle • High • Very High
Energy resource potentials	• Water treatment plant • Waste incineration plant • Industrial waste heat (data centre) • Existing geothermal probes
Infrastructure	• District heating • Gas grid • Waste treatment plant • Waste water treatment plant • Biogas plant • Data center • Sewage pipes > 800mm

Decarbonisation approaches	***Classification***
Supply solutions and additional categories	• Existing thermal network • Foreseen thermal network • Individual heating solutions • Surface geothermal • Groundwater, ambient air-heat pump • Areas suitable for small thermal network (small scale) • Industrial zones (gas for processes available) • Areas with cooling demand 

The final decarbonisation approach is then classified into different supply solutions for areas, including a focus on thermal networks (district heating), individual heating solutions or gas for process energy as well as areas with cooling demand.

Design approaches for a database-driven urban typology

This chapter presents the data used, the methodology applied, and the steps taken to create a database-driven urban typology. In addition to the typology developed, a set of six design approaches were derived for the different urban typologies, two per reference typology. Furthermore, the seven cities involved in the DCP project were characterised according to the criteria used for the typology. This city-specific characterisation and a cross-city synthesis can be found in Deliverable 2.6 “H/C outlook 2050 in each participating city and cross-city synthesis”. Overall the aim of this chapter is to develop design approaches or solutions for different types of areas (cities, districts etc.) with a focus on how decarbonisation can be achieved. Accordingly, this chapter starts with the underlying data and methodology, followed by the presentation of the newly developed typology and ends with the specific design approaches.

Underlying data and applied methodologies

In a first step the structuring criteria, the underlying data sources, and the *Analytic Hierarchy Process* (AHP), as the main methodology are explained below. There are diverse measures and evaluation criteria that should be taken into account when the transformation to decarbonized urban heating and cooling systems is aimed. These indicators are essential when defining urban typologies and subsequently elaborating the corresponding decarbonisation design approaches. The pertinent criteria should somehow be chosen according to their relevance and importance. Moreover, to define the typologies based on the seven under-study cities, merely those measures for which reliable data are accessible should be considered. In total, 10 structuring criteria were used as a basis. The criteria are explained in more detail in Table 9, comprising city population, heating index, heat demand density, individual energy efficiency, structural energy efficiency, dependency on fossil fuels, potential for renewable sources, potential for waste heat, development of the built environment and the coverage of district heating. These indicators have been selected in keeping with the urban heating and cooling literature and regarding data availability. The specific data sources for the criteria are listed in Deliverable 2.6 “H/C outlook 2050 in each participating city and cross-city synthesis”.

TABLE 9 : OVERVIEW STRUCTURING CRITERIA FOR THE DEVELOPMENT OF THE DATABASE-DRIVEN TYPOLOGY (MORE DETAILS CAN BE FOUND IN DELIVERABLE 2.6)

Structuring Criteria	*Description*	*Definition*
City population	Projected city population in 2050	Calculated as the relative difference between projected 2050 population and known 2015 population at hectare level
Heating index	An adjusted version of the ordinary Heating Degree Day concept, which, among other, takes into consideration the typical level of building insulation used in different European countries	The index is calculated based on 40 years' time-series data with sub-hourly measurements and established the local average for the given time period
Heat Demand Density	The spatial concentration of building heat demands for space heating and domestic hot water preparation, often expressed as MWh per hectare or similar	Calculated as the share of hectare cells out of the urban area total with heat demand densities above 120 TJ/km2 under the sEEnergies Frozen Efficiency scenario (FE2050)
Individual energy efficiency	Energy efficiency measures with end-use application address, typically energy savings in buildings by, for example, refurbishments, window replacements, increased insulation, etc.	The sEEnergies Index sub-index “Building Efficiency” establishes a quota between projected 2050 building heat demands in a (more ambitious) Baseline scenario (BL2050) and a (more modest) Frozen Efficiency scenario (FE2050). This fraction is then subtracted from the number “one” (thus expressing the potential for individual energy efficiency as a percentage) and assigned a value between 1 and 10 by classification.
Structural energy efficiency	Energy efficiency measures applied on the supply side of the energy system which obtains reduced primary energy demands by more efficient conversion and distribution (for example, district heating systems)	Calculated as the share of total urban area building heat demands, by hectare grid cells, that permits investments in district heating networks with marginal distribution capital costs at or below 10 €/GJ under the sEEnergies Baseline scenario (BL2050)
Dependency on fossil fuels	Current and future dependency on natural gas, oil, coal, and other fossil sources for heating and cooling purposes in buildings	Sum of "Gas" and "Oil" in the city as stated in internal project report
Potential for renewable sources	Local/regional potential for renewable energy sources, such as sustainable biomass, geothermal, solar energy, etc.	Expresses Reference scenario potential for biomass in 2050, apportioned to urban areas by 50 km and 100 km radius from city centres
Potential for waste heat	Local/regional potential for waste heat, considering all possible sources such as power plants, iron works, paper and pulp plants, data centres, wastewater treatment plants, etc	Current potentials for conventional and unconventional sources, inside, within 10 km, and within 25 km of urban area perimeters
Development of the built environment	The expected development of the built environment with respect to residential and service sectors expressed as the modelled evolution of floor areas	Calculated as the relative difference between projected 2050 floor areas and known 2015 floor areas at hectare level
Coverage of district heating	Current and future deployment level of district heating	Current relative shares in the city as stated in internal project report

The criteria in

Table 9 may not be of equal importance in designing approaches to decarbonize urban heating and cooling. To rank and prioritize the measures in terms of their significance to the problem, a multi-criteria decision analysis (MCDA) has been employed. MCDAs are promising, wildly used tools generally to recognize the best choices in the presence of multiple indicators. One commonly used MCDA method is the analytic hierarchy process (AHP). Developed by Saaty (1987) to organize and solve complex decisions, the method has received extensive applications in analyzing energy problems (Abdul et al. 2022). The method's underlying idea is to overcome a complicated decision-making problem by reducing it to a series of straightforward pairwise comparisons. The function of AHP, in particular, is to deal with the verbal judgments of experts about an issue and convert these judgments into quantitative weights applicable to numerical analysis.

The AHP method is composed of three steps: 1) structuring of the decision-making problem in a hierarchy, 2) pairwise comparisons between the elements at each level of the hierarchy, and 3) calculation of priorities (weights) (Väisänen et al. 2016).

Step 1. Structuring the decision-making problem

AHP configures the decision problem in a hierarchical tree with three primary levels of goal, criteria, and alternatives. The goal refers to the problem that should be solved, the alternatives are all the possible solutions, and the criteria imply evaluation metrics on which the alternatives are judged. These elements of the AHP are connected to each other from up to down according to the problem specifications providing the decision matrix. However, the method is flexible to have more or less than the three default levels. This relates to situations in which there are no alternatives (and only the weight and ranking of the criteria matter), or there are different levels of criteria (criteria and sub-criteria). The method also has an advantageous ability to support both individual and group decision-making.

The hierarchy tree of the concerned problem is designed in three levels. The first level is the goal which is the decarbonization of urban heating and cooling systems. The second level includes the main categories of the criteria (i.e., energy supply, energy demand, and energy efficiency). The third level encompasses the ten structuring criteria. Accordingly, the AHP hierarchy tree is formed as in Figure 3.

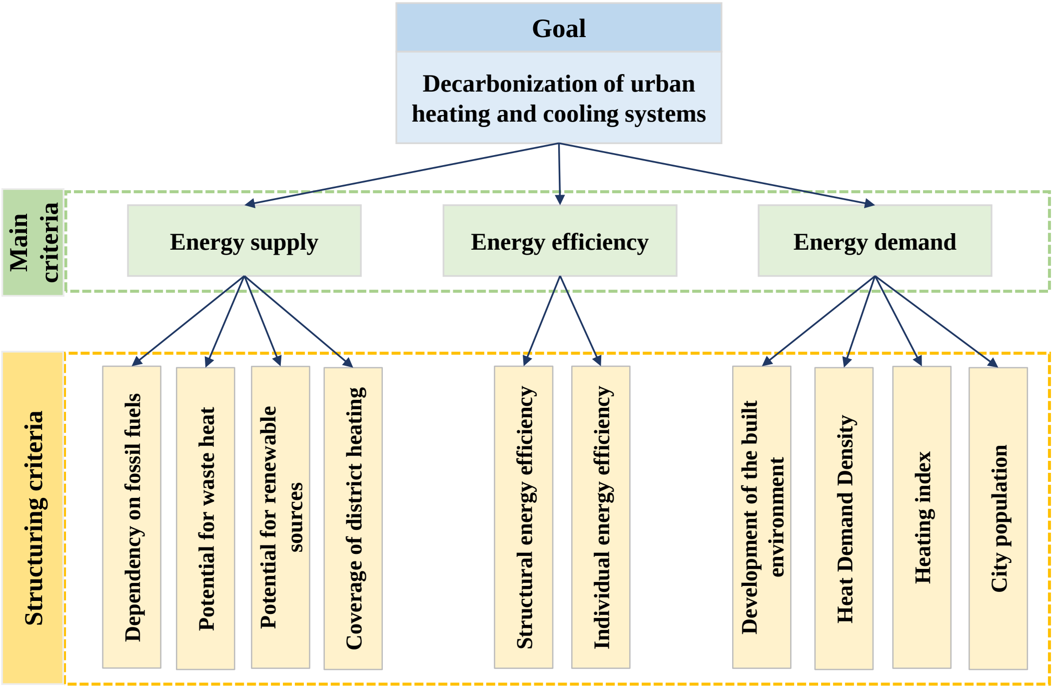


FIGURE 3 : THE DEVELOPED AHP HIERARCHY TREE FOR THE DECARBONIZATION OF URBAN HEATING AND COOLING SYSTEMS

Step 2. Pairwise comparisons

Determining the weights of decision elements (criteria and alternatives) in the AHP is based on pairwise comparisons of the linked elements regarding a controlling factor from an upper level. The pairwise comparison is the initiative of the method as Saaty (2008) discussed that mentally and psychologically, it is easier to compare the available options pair by pair when they are numerous. A numerical scale from one to nine is applied to express the relative importance in the comparisons, where the larger number, the higher importance. The scale and the interpretation of the values are provided in Table 10. The AHP method benefits also from an "inconsistency ratio" index, which assesses the reasonability of the pairwise comparisons. The judgments are reliable enough if the inconsistency ratio is below 10% (Saaty 2008).

TABLE 10 : DEFINITION AND DESCRIPTION OF AHP EVALUATION SCALE

Verbal judgment	*Numerical value*
If criterion i and criterion j are equally important	1
If criterion i is slightly more important than criterion j	3
If criterion i is clearly more important than criterion j	5
If criterion i is strongly more important than criterion j	7
If criterion i is extremely more important than criterion j	9
Intermediate judgements	2, 4, 6, 8

Based on the constructed hierarchy tree in Figure 3, a questionnaire consisting of pairwise assessments of the criteria categories and structuring criteria was designed as is presented in the appendix. A description of the criteria was included in the survey to keep the respondents aware of how each criterion is interpreted in the concerned problem. Moreover, a short instruction about comparing the elements was provided. The questionnaire entails 16 statements or pairwise comparisons divided into four tables. The first table compares the importance of the criteria categories regarding the goal, i.e., decarbonization of urban heating and cooling systems. The other three tables are designed to judge the relative significance of structuring criteria in each of the three criteria categories.

Step 3. Calculation of priorities

Twenty-one energy experts including professors, and researchers, consultants, and project partners, from three universities (Halmstad University (SE), Lund University (SE), Aalborg University (DK)), four city administrations (City of Vienna (AT), City of Munich (DE), City of Rotterdam (NL), City of Winterthur (CH)), and three other institutions and consultancies (Urban Innovations Vienna (AT), Technalia (ES), Codema (Dublin Energy Agency) (IE)), were asked to participate in the survey and fill out the questionnaire. Among these, 12 completed questionnaires were collected, which corresponds to a response rate of almost 60%. The participants' responses were aggregated by geometric mean to reach the group decision matrix, and the Super Decisions software (2022) was used to carry out the calculations. The inconsistency ratio of the aggregated decision matrix was obtained as 1%, which is below 10% and thus acceptable.

The results as relative weights of the criteria categories and the structuring criteria are represented in Figure 4 and Figure 5. Figure 4 shows that with 52% weight, the energy supply is the most crucial main criterion for decarbonizing urban heating and cooling systems, followed by energy efficiency (30%) and energy demand (18%). As seen in Figure 5, as a result of the higher priority of energy supply and energy efficiency, those structuring criteria which are associated with these two main categories have received further emphasis from experts. Interestingly, three indicators have achieved very similar results with weights around 8 and 9 (Heat demand density: 9.0, dependency on fossil fuels: 8.8, individual energy efficiency: 8.6).

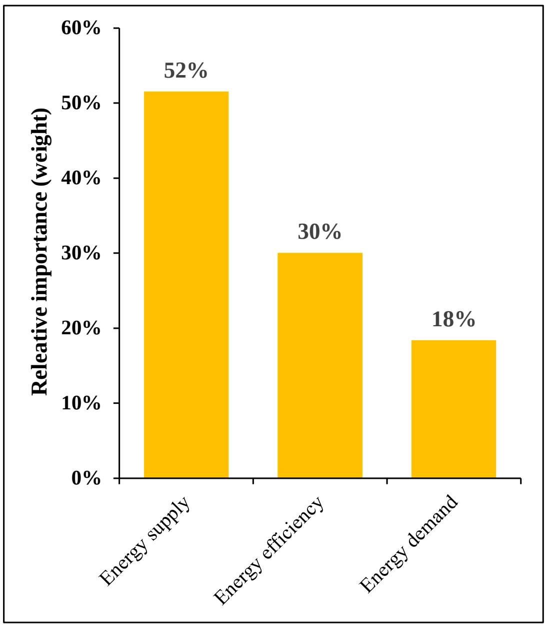


FIGURE 4 : THE WEIGHTS OF THE THREE MAIN CRITERIA FOR THE DECARBONIZATION OF URBAN HEATING AND COOLING SYSTEMS BASED ON THE EXPERTS' OPINIONS

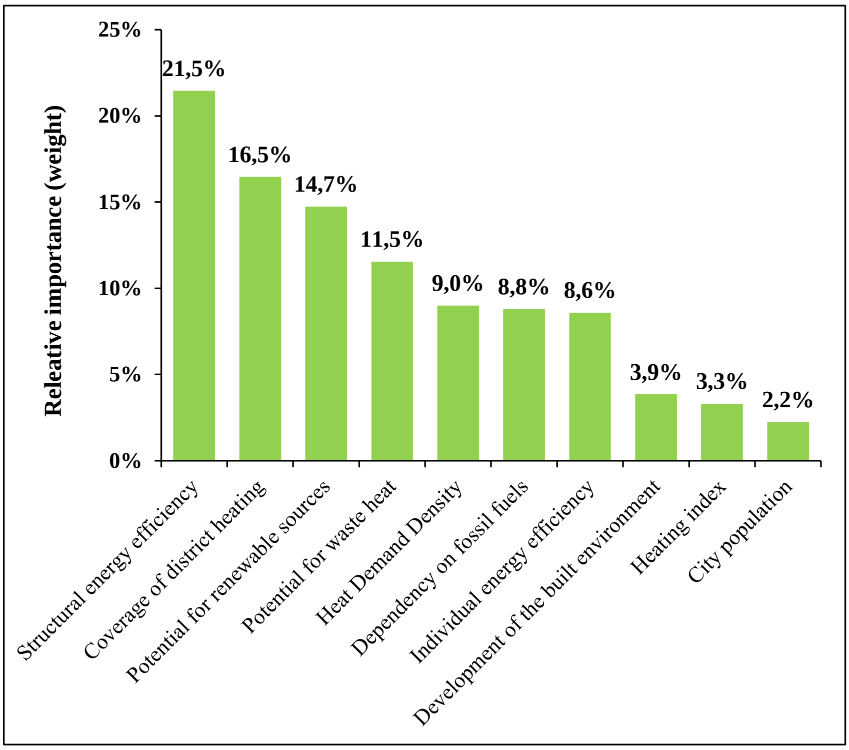


FIGURE 5 : THE WEIGHTS OF THE STRUCTURING CRITERIA FOR THE DECARBONIZATION OF URBAN HEATING AND COOLING SYSTEMS BASED ON THE EXPERTS' OPINIONS

Development of the database-driven urban typology

In addition to the weighting of the criteria (which was done with the help of the AHP), a classification of each criteria was made. Class "A" represent high compatibility with highly weighted criteria whereas class "D" represents low compatibility with highly weighted criteria. Further details on this classification and the underlying calculations can be found in Deliverable 2.6 "H/C outlook 2050 in each participating city and cross-city synthesis". Additionally, Deliverable 2.6 provides a detailed classification of the cities involved in the DCP project as well as a cross-city synthesis.

Table 11 shows the applied classification of each structuring criterion, divided into "A", "B", "C" or "D". The last column contains the AHP weights as a result of the expert survey (criteria sorted from high to low weighting). The weights indicate the relative importance of the individual criteria. The higher the value, the more important the criterion in question, compared to the other criteria. In total, the sum of weights equals one. The classification is based on data for the seven DCP Cities (also see D2.6 for further details).

TABLE 11 : CRITERIA INCLUDING CLASSIFICATION AND THEIR RELATIVE IMPORTANCE BASED ON AHP WEIGHTS

Structuring Criteria	***Classification***				***AHP weight*** *(high to low)*
	A	***B***	***C***	***D***	

Structural energy efficiency	*More than +30% relative cities average*	*Up to +30% relative cities average*	*Down to -30% relative cities average*	*Below -30% relative cities average*	***21.5%***
Coverage of district heating	*More than +50% relative cities average*	*Up to +50% relative cities average*	*Down to -50% relative cities average*	*Below -50% relative cities average*	***16.5%***
Potential for renewable sources	*More than +50% relative cities average*	*Up to +50% relative cities average*	*Down to -50% relative cities average*	*Below -50% relative cities average*	***14.7%***
Potential for waste heat	*More than +50% relative cities average*	*Up to +50% relative cities average*	*Down to -50% relative cities average*	*Below -50% relative cities average*	***11.5%***
Heat Demand Density	*More than +20% relative cities average*	*Up to +20% relative cities average*	*Down to -20% relative cities average*	*Below -20% relative cities average*	***9.0%***
Dependency on fossil fuels	*Below -25% relative cities average*	*Down to -25% relative cities average*	*Up to +25% relative cities average*	*More than +25% relative cities average*	***8.8%***
Individual energy efficiency	*More than +50% relative cities average*	*Up to +50% relative cities average*	*Down to -50% relative cities average*	*Below -50% relative cities average*	***8.6%***
Development of the built environment	*Below -25% relative cities average*	*Down to -25% relative cities average*	*Up to +25% relative cities average*	*More than +25% relative cities average*	***3.9%***
Heating index	*Below -5% relative cities average*	*Down to -5% relative cities average*	*Up to +5% relative cities average*	*More than +5% relative cities average*	***3,3%***
City population	*2050 decrease relative 2015 at or below -20%*	*2050 decrease relative 2015 down to -20%*	*2050 increase relative 2015 up to 20%*	*2050 increase relative 2015 at or above 20%*	***2,2%***

As mentioned above, the Super Decisions software was used to generate the AHP results. The underlying calculations for the classifications and the development of the typology were done in Excel (see Figure 6).

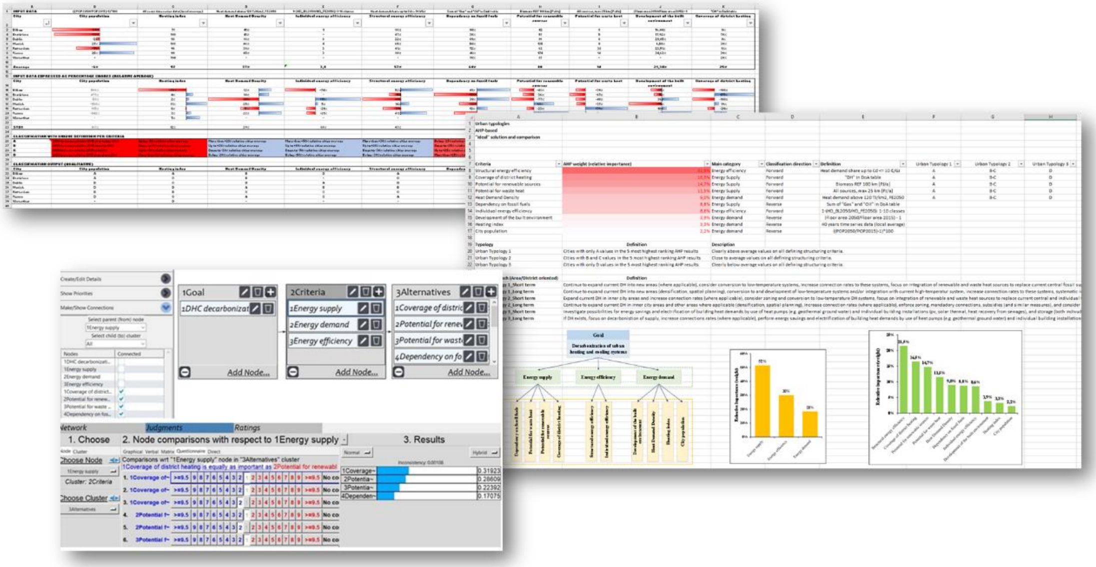


FIGURE 6 : PREPARATION OF STRUCTURING CRITERIA AND TYPOLOGY

Before presenting the urban typology itself, the underlying classification needs to be examined in more detail. During developing the typology, the question arose as to whether the classification results should be interpreted as positive or negative. Accordingly, the following objective was adhered to: Decarbonisation of heating and cooling sector until 2050. In addition, the typology can be used for entire cities as well as for individual districts. Therefore, the typology works independently of the spatial resolution. In this way, the typology is broadly applicable and the design approaches do not only apply to a previously defined spatial unit. However, if an assessment is made for certain urban areas and not for the entire city, the following must be taken into account: Data for the “A” to “D” ratings is from the participating DCP cities. Hence, a classification on district level for instance would generate quite different results. Additionally, the weighting results of the criteria would look different accordingly.

It should also be noted that the ratings from A to D are very context-dependent. This is especially true for the criteria “heating index”, “city population” and “development of the built environment”. Depending on the spatial resolution or the underlying objective, the rating may differ. For example, a high heating index is directly related to a high heating demand. For a whole city, this means that more energy demand needs to be decarbonised. However, for certain areas, a high heating demand can be beneficial to make district heating more economical (higher connection rates, etc.). Another example is population growth. Densification within the city (inner-city development) is beneficial for decarbonisation, whereas urban sprawl is not.

For the mentioned context-dependent criteria, and for the criteria “dependency on fossil fuels” an inverse order of ratings was applied. A very strong decrease was rated “A”, a comparably strong increase was rated “D”. This hierarchy is obvious for the dependency on fossil fuels. High dependence is not beneficiary for decarbonisation. However, the inverse order of the three context dependent criteria, is based on the main criterion, energy demand. High energy demand is definitely not beneficial for decarbonisation. Therefore, the heating index, the city population and the development of the built environment were also given an inverse rating.

The final urban heating and cooling typology is based on the scores (weights) of the AHP results and is presented as an overview in Figure 7. The underlying idea was to develop a typology representing ideal (extreme) cases. In addition to the AHP weights, the typology is also based on the corresponding classification of the individual criterion. The result is a typology consisting of three types:

- Urban H/C Type 1
- Urban H/C Type 2
- Urban H/C Type 3

As Figure 7 shows, Urban H/C type 1 represents areas with only "A" ratings in the 5 highest ranked AHP outcomes. This means that this type comprises clearly above average values on all defining structuring criteria. The second type (Urban H/C Type 2) reflects areas with "B" and "C" ratings in the 5 highest ranking AHP outcomes. This means that this type comprises close to average values on all defining structuring criteria. Finally, the Urban H/C Type 3 represents areas that have only "D" classifications in the 5 highest ranked AHP results. This means that this type comprises clearly below average values on all defining structuring criteria. The five highest ranked criteria are:

- Structural energy efficiency (AHP: 21.5%)
- Coverage of district heating (AHP: 16.5%)
- Potential for renewable sources (14.7%)
- Potential for waste heat (11.5%)
- Heat Demand Density (9.0%)

Urban H/C Type 1	Urban H/C Type 2	Urban H/C Type 3
• **A rating** in Structural energy efficiency	• **B or C rating** in Structural energy efficiency	• **D rating** in Structural energy efficiency
• **A rating** in Coverage of district heating	• **B or C rating** in Coverage of district heating	• **D rating** in Coverage of district heating
• **A rating** in Potential for renewable sources	• **B or C rating** in Potential for renewable sources	• **D rating** in Potential for renewable sources
• **A rating** in Potential for waste heat	• **B or C rating** in Potential for waste heat	• **D rating** in Potential for waste heat
• **A rating** in Heat Demand Density	• **B or C rating** in Heat Demand Density	• **D rating** in Heat Demand Density

FIGURE 7 : OVERVIEW OF DATA BASE DRIVEN URBAN TYPOLOGY

To better understand the typology developed, the following three figures show sample visualisations of the heat demand densities for each Urban H/C type.

Figure 8 illustrates **Urban H/C Type 1** which is characterised by high heat demand density, high structural energy efficiency as well as high coverage of district heating, high potential for renewable sources and high potential for waste heat ("A" ratings in the 5 highest ranked AHP outcomes).

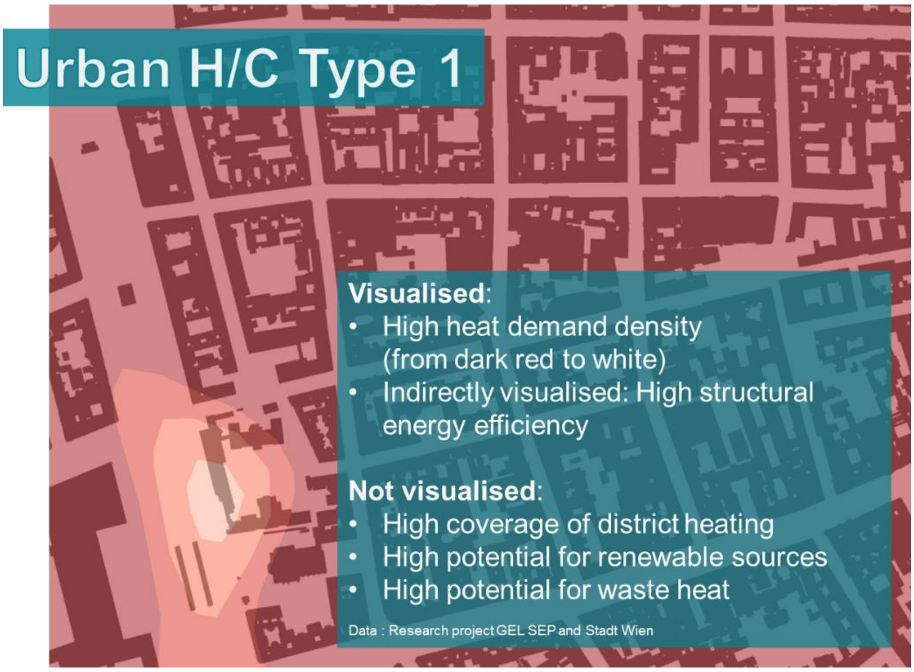


Figure 8 : Visualisation of Urban H/C Type 1

Figure 9 shows **Urban H/C Type 2** which is characterised by average heat demand density, average structural energy efficiency as well as average coverage of district heating, average potential for renewable sources and average potential for waste heat ("B" or "C" ratings in the 5 highest ranked AHP outcomes).

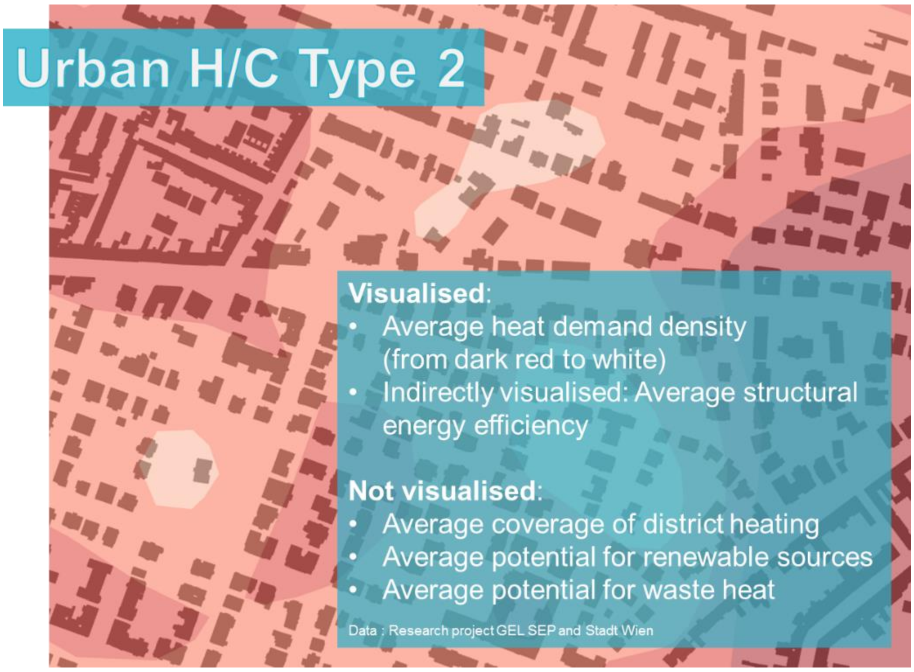


Figure 9 : Visualisation of Urban H/C Type 2

Finally, Figure 10 highlights **Urban H/C Type 3** which is characterised by low heat demand density, low structural energy efficiency as well as low coverage of district heating, low potential for renewable sources and low potential for waste heat ("D" ratings in the 5 highest ranked AHP outcomes).

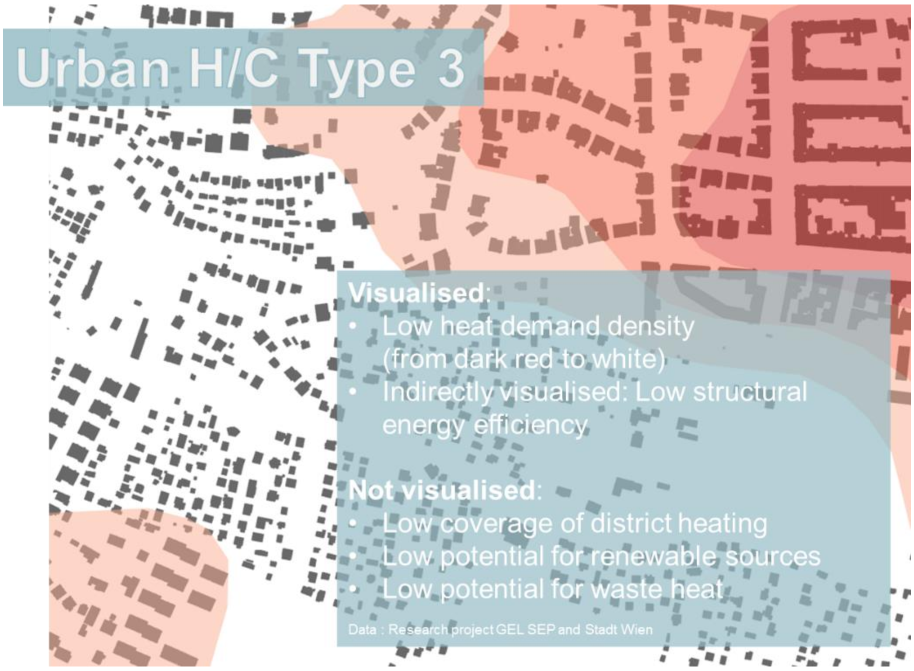


FIGURE 10 : VISUALISATION OF URBAN H/C TYPE 3

With regard to the participating cities of the DCP project, a detailed evaluation was carried out in Deliverable 2.6 "H/C outlook 2050 in each participating city and cross-city synthesis". Among others there is a detailed classification of each city using the presented structuring criteria as well as a comprehensive cross-city synthesis including detailed maps and visualisation of parameters not included in this report.

The methodology presented is applicable to different cities or parts of cities. Hence, the typology refers to cities as such or to city districts, neighbourhoods or simply to areas that need to be decarbonised. The reason why this approach was chosen was, on the one hand, to develop design approaches that would be valid not only for the participating cities, but for all cities, city districts and urban areas in Europe. In parallel, decarbonisation strategies at neighbourhood level are also developed by the participating cities, as also summarised for example in the chapter "Decarbonisation approaches in the DCP cities" of this report and in Deliverable 3.3 „H/C Plans of Cities with Cross-city synthesis". In addition, cities are encouraged to create their own typologies based on the structuring criteria and the AHP results presented in this report. It is the ambition that this database-driven urban typology assessment method will find plentiful use among cities and towns in Europe.

Design approaches for urban H/C typologies

In this last step, two design approaches were derived for each of the three database-driven typologies, resulting in a total of six design approaches. The approaches have partly been elaborated on particular local conditions in the participating DCP cities, but also on more general principles of heat planning. They were created to identify possible solutions and recommendations for each type on how to achieve decarbonisation of the heating and cooling sector. The design approaches include strategic pathways combined with concrete proposals for decarbonisation measures and are kept compact so as not to lose the overview. Accordingly, the individual design approaches are explained in more detail below. The first design-approach for each type always represents short-term solutions (until 2030) while the second design approach includes long-term solutions (2050).

Short-term design approach for **Urban H/C Typology 1:**

The first design approach addresses short-term solutions and recommendation for Urban H/C Typology 1. This typology mainly refers to central supply solutions. Accordingly, the following solutions and recommendations for this type are emphasised:

- *Where applicable, continue to expand current district heating into new areas*
- *Start to consider and plan for conversion to low-temperature district heating systems*
- *Increase connection rates to these systems*
    - *Supply areas that are close to the already existing network but not yet connected*
    - *"Fill in the gaps" where district heating is not yet established but the conditions for district heating are met*
- *Focus on integration of renewable and waste heat sources to replace current central fossil supply*
    - *Promising technologies include deep geothermal energy and large-scale heat pumps for decarbonising the district heating system*
    - *Using additional shallow geothermal energy*
    - *All kinds of waste heat sources (also low temperature waste heat)*
    - *Sustainable biomass (residues from forestry and agriculture, gasification etc.)*
    - *Water bodies if in vicinity*
- *Investigate potentials for district cooling (decision if a new infrastructure will cost more as single cooling solutions)*
- *Decision which area should be disconnected from gas and when*

Long-term design approach for **Urban H/C Typology 1:**

The second design approach addresses long-term solutions and recommendation for Urban H/C Typology 1. This typology mainly refers to central supply solutions. Accordingly, the following solutions and recommendations for this type are emphasised:

- *Continue to expand current district heating into new areas*
    - *Focus on densification of the built environment*
    - *Focus on long term urban planning strategies (try to supply different functions, densification measures etc.)*

- *Coordination of the expansion of DH with stopping the gas supply in some areas*
- *Conversion to and development of low-temperature systems and/or integration with current high-temperature system*
  - *Increase central district heating network by incorporating stand-alone district heating systems into the central district heating network*
- *Enforce systems where cooling and heating is possible (e.g. low temperature floor heating supplied by heat pumps using shallow geothermal energy). If not, district cooling could be an option (comparison with other cooling solutions / district cooling is a new and expensive infrastructure)*
- *Increase connection rates to these systems*
  - *Supply areas that are close to the already existing network but not yet connected*
- *Systematic integration of renewable and waste heat sources to replace current central fossil supply*
  - *Promising technologies include deep geothermal energy and large-scale heat pumps for decarbonising the district heating system*

Short-term design approach for **Urban H/C Typology 2:**

The third design approach addresses short-term solutions and recommendation for Urban H/C Typology 2. This typology refers to both central and individual supply solutions. Accordingly, the following solutions and recommendations for this type are emphasised:

- *Where applicable expand current district heating in inner city areas and increase connection rates*
  - *Focus mainly on areas with high energy demand densities*
- *Consider zoning and conversion to low-temperature district heating systems – it could be decentralised including new DH networks connected to each other or to a centralised DH*
- *Focus on integration of renewable and waste heat sources to replace current central and individual fossil supply*
  - *Special focus on electrification, geothermal energy etc.*
- *Decision which area should be disconnected from gas and when*

Long-term design approach for **Urban H/C Typology 2:**

The fourth design approach addresses long-term solutions and recommendation for Urban H/C Typology 2. This typology refers to both central and individual supply solutions. Accordingly, the following solutions and recommendations for this type are emphasised:

- *Continue to expand current district heating in inner city areas and other areas where applicable*
  - *Focus on densification via spatial planning*
- *Where applicable increase connection rates*
- *Enforce energy related zoning*
  - *Zoning may include mandatory connection to district heating or specific subsidies for these areas*
- *Consider conversion to low-temperature district heating systems*
- *Focus on integration of renewable and waste heat sources to replace current central and individual fossil supply*
  - *Special focus on electrification, geothermal energy etc.*

Short-term design approach for **Urban H/C Typology 3:**

The fifth design approach addresses short-term solutions and recommendation for Urban H/C Typology 3. This typology mainly refers to individual supply solutions. Accordingly, the following solutions and recommendations for this type are emphasised:

- *Investigate possibilities for energy savings*
    - *Refurbishment activities*
    - *Replacing old heat supply systems in buildings*
- *Focus on electrification of building heat demands by use of heat pumps*
    - *Further focus on shallow geothermal energy and ground water heat recovery etc.*
- *Focus on individual building installations*
    - *Focus on photovoltaic, solar thermal energy, heat recovery from sewages etc.*
- *Focus on individual and central energy storage solutions*

Long-term design approach for **Urban H/C Typology 3:**

The sixth design approach addresses long-term solutions and recommendation for Urban H/C Typology 3. This typology mainly refers to individual supply solutions. Accordingly, the following solutions and recommendations for this type are emphasised:

- *If district heating exists, focus on decarbonisation of supply*
- *Decentralise the energy system - in some cases of centralised district heating it could be useful to convert it to a decentralised network or to renewable single solutions to have enough "power" for central DH supply of very dense areas*
- *Where applicable increase connections rates*
- *Perform energy savings – enforce refurbishments especially if only low-temperature grids or renewable single solutions are possible*
- *Focus on programs for high-efficiency buildings (passive houses, etc.)*
- *Focus on geothermal probes as also storage systems combined with solar thermal recovery etc.*
- *Make use of gasification (by using existing infrastructure) based on residues from forestry and agriculture etc.*
- *Focus on electrification of building heat demands by*
    - *using heat pumps such as (e.g. geothermal ground water) and*
    - *individual building installations such as photovoltaic, solar thermal energy, heat recovery from sewages etc.*
- *Improve sector coupling to improve structural energy efficiency*
- *Focus on individual and central energy storage solutions*

The main benefit of the presented design-approaches is a comprehensible, simple and easily understood architecture for actions that can be considered to decarbonise cities and urban areas in general. However, it must also be noted that the "design approaches" are not so detailed and comprehensive that they can be used to clarify every question regarding the decarbonisation of a district or sub-area. The design approaches are not a substitute for detailed planning.

Summary

This report identifies different typology-based approaches and methods for decarbonising the energy sector of cities. Respectively, typologies were evaluated and design approaches were developed. In a first step, already existing typologies were evaluated, including a study by the Technical University of Darmstadt and examples from the City of Vienna. In a next step, conceivable structuring criteria and decarbonisation approaches from existing work within the DCP project were identified and summarised. These include structuring criteria such as heat demand density, renewable energy sources or types of refurbishment activities. On this basis, a new typology was developed.

Five highly weighted criteria could be derived from the results of the expert survey, including structural energy efficiency, coverage of district heating, potential for renewable sources, potential for waste heat and heat demand density. These criteria formed the basis for the development of the novel typology. The first typology represents areas with high compatibility with highly weighted criteria, the third typology represents areas with comparably low compatibility, while the second typology is associated in between. Based on the developed typology, six design approaches were presented in this report. One short-term and one long-term approach for each typology include recommendations as well as concrete measures for strategic decision-making.

In summary, this report has highlighted how cities can proceed in decarbonising the energy sector. Accordingly, all cities are encouraged to either develop their own typology for decarbonisation or simply make use of the condensed content of this report for their own goals towards decarbonisation.

This report is the first of three reports under Work Package 2 of the DCP project, with a focus on urban typologies, design approaches, H/C outlooks for 2050, cross-city synthesis and a final recommendation for cities. The work presented in this report will be continued in Deliverable 2.6 “H/C outlook 2050 in each participating city and cross-city synthesis” and in Deliverable 2.7 “Recommendations with respect to expected H/C supplies & demands in 2050 for cities”.

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Appendix – Questionnaire used for the Analytical Hierarchy Process

Decarb city pipes questionnaire/Decarb City Pipes 2050
Halmstad University (SE) & City of Vienna (AT)
August 2022

Decarb city pipes questionnaire

Pairwise comparison of strategic criteria for decarbonised heating and cooling systems in European cities

The purpose of this questionnaire is to gather experts' opinions about the relative importance of different criteria regarding their influence on the transformation and decarbonisation of heating and cooling systems in European urban areas, such as towns, cities, and larger metropolitan areas. The assembled responses will be used to calculate weights for these criteria in an Analytical Hierarchy Process (AHP), which then will be used to define a set of urban typologies and decarbonisation design approaches. Your personal responses will not be disclosed in any context and your participation is completely voluntary.

Separate accounts of the approach, the weights, other used data, and summaries of the results, are anticipated to be presented in deliverable reports D2.5, D2.6, and D2.7, in the EU-horizon 2020 project "Decarb City Pipes 2050", Decarb City Pipes 2050 – Phase-out fossil fuels from urban heating & cooling (to be made publicly available during the autumn of 2022).

Objective and criteria

As a respondent, consider a general context in which a European city (explicit focus on urban areas here, excluding rural and country-side areas) wants to reduce its use and dependency on fossil fuels for heating and cooling of buildings. In other words, a city seeks to decarbonise its supply and distribution of energy to meet low-temperature energy demands in the residential and service sectors. The target year for this transformation is 2050.

Table 1 presents the three main categories (Energy supply, Energy demand, and Energy efficiency) by which the ten strategic criteria are divided for the pairwise comparisons.

Table 1. The considered criteria and their definition

Category	Criterion	Definition
Energy supply	Coverage of district heating	Current and future deployment level of district heating.
	Potential for renewable sources	Local/regional potential for renewable energy sources, such as sustainable biomass, geothermal, solar energy, etc.
	Potential for waste heat	Local/regional potential for waste heat, considering all possible sources such as power plants, iron works, paper and pulp plants, data centers, wastewater treatment plants, etc.
	Dependency on fossil fuels	Current and future dependency on natural gas, oil, coal, and other fossil sources for heating and cooling purposes in buildings.
Energy demand	City population	Projected city population in 2050.
	Heating index	An adjusted version of the ordinary Heating Degree Day concept, which, among other, takes into consideration the typical level of building insulation used in different European countries.
	Heat Demand Density	The spatial concentration of building heat demands for space heating and domestic hot water preparation, often expressed as MWh per hectare or similar.
	Development of the built environment	The expected development of the built environment with respect to residential and service sectors expressed as the modelled evolution of floor areas.
Energy efficiency	Individual energy efficiency	Energy efficiency measures with end-use application address, typically energy savings in buildings by, for example, refurbishments, window replacements, increased insulation, etc.
	Structural energy efficiency	Energy efficiency measures applied on the supply side of the energy system which obtains reduced primary energy demands by more efficient conversion and distribution (for example, district heating systems).

1

Questionnaire

In your expert opinion, how important are the considered criteria for a successful transition to a decarbonised urban heating and cooling system?

Please provide answers for each pairwise comparison outlined in Tables 3 to Table 6 below.

For each row of the questionnaires, we kindly ask you to compare each criterion i with each criterion j and indicate your evaluation of each pairwise comparison. The pairwise comparison scale as outlined in Table 2 is used to express the importance of one element over another.

Table 2. Definition and description of AHP evaluation scale

Explanation	Numerical value
If criterion i and criterion j are equally important	1
If criterion i is slightly more important than criterion j	3
If criterion i is clearly more important than criterion j	5
If criterion i is strongly more important than criterion j	7
If criterion i is extremely more important than criterion j	9
Intermediate judgements	2, 4, 6, 8

- The more important the criterion on the left (criterion i), select and mark (by highlight colour, underline, or similar) a larger number on the left. Vice versa, the more important the criterion on the right (criterion j), select and mark a larger number on the right.
- If both criteria in a row have equal importance, mark "1".
- Put only one mark on each row.

Table 3. Pairwise comparisons of criteria corresponding to the decarbonisation of urban heating & cooling

	In transition to a **DECARBONISED URBAN HEATING & COOLING SYSTEM**, please indicate the relative importance of criteria category i (left column) to criteria category j (right column).																		
ID	Criteria category i	Importance																	Criteria category j
3a	Energy supply	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Energy demand
3b	Energy supply	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Energy efficiency
3c	Energy demand	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Energy efficiency

Table 4. Pairwise comparisons of criteria corresponding to energy supply

	With respect to **ENERGY SUPPLY** criteria to decarbonise urban heating and cooling, please indicate the relative importance of criterion i (left column) to criterion j (right column).																		
ID	Criterion i	Importance																	Criterion j
4a	Coverage of district heating	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Potential for renewable sources
4b	Coverage of district heating	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Potential for waste heat
4c	Coverage of district heating	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dependency on fossil fuels
4d	Potential for renewable sources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Potential for waste heat
4e	Potential for renewable sources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dependency on fossil fuels
4f	Potential for waste heat	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dependency on fossil fuels

Table 5. Pairwise comparisons of criteria corresponding to energy demand

	With respect to **ENERGY DEMAND** criteria to decarbonise urban heating and cooling, please indicate the relative importance of criterion i (left column) to criterion j (right column).																		
ID	Criterion i	Importance																	Criterion j
5a	City population	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Heating index
5b	City population	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Heat Demand Density
5c	City population	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Development of the built environment
5d	Heating index	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Heat Demand Density
5e	Heating index	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Development of the built environment
5f	Heat Demand Density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Development of the built environment

Table 6. Pairwise comparisons of criteria corresponding to energy efficiency

	With respect to **ENERGY EFFICIENCY** criteria to decarbonise urban heating and cooling, please indicate the relative importance of criterion i (left column) to criterion j (right column).																		
ID	Criterion i	Importance																	Criterion j
6a	Individual energy efficiency	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Structural energy efficiency

DECARB CITY PIPES 2050

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 893509