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Work Package 4 | Task 4.2

# D4.3 - Report on infrastructure requirements for developing sustainably PEDs, summarizing the outcome of the techno-economic modelling activities

Smart - BEEjS
Human - Centric
Energy Districts

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# About the Smart-BEEjS Project

The **overarching aim of Smart-BEEjS** is to provide, through a multilevel, multidisciplinary and interdisciplinary research and training, a programme to produce the technology, policy making and business oriented **transformative and influential champions of tomorrow**. Educated in the personal, behavioural and societal concepts needed to deliver the success of any technological proposition or intervention under a human-centric perspective.

The Smart-BEEjS presents a balanced consortium of beneficiaries and partners from different knowledge disciplines and different agents of the energy eco-system, **to train at PhD level** an initial generation of **transformative and influential champions** in policy design, techno-economic planning and Business Model Innovation in the energy sector, **mindful of the individual and social dimensions**, as well as the **nexus of interrelations between stakeholders** in energy generation, technology transition, efficiency and management. Our aim is to boost knowledge **sharing across stakeholders, exploiting a human-centric and systemic approach to design Positive Energy Districts** (PEDs) for sustainable living for all. The SMART-BEEjS project recognises that the new level of decentralisation in the energy system requires the systemic synergy of the different stakeholders, balancing attention towards technological and policy oriented drivers from a series of perspectives:

- **Citizens and Society,** as final users and beneficiaries of the PEDs;
- **Decision Makers and Policy Frameworks,** in a multilevel governance setting, which need to balance different interests and context-specific facets;
- **Providers of Integrated Technologies, Infrastructure and Processes of Transition,** as innovative technologies and approaches, available now or in the near future; and,
- **Value generation providers and Business Model Innovation (BMI)** for PEDs and networks of districts, namely businesses, institutional and community initiated schemes that exploit business models (BMs) to provide and extract value from the system.

The stakeholders of this ecosystem are inseparable and interrelate continuously to provide feasible and sustainable solutions in the area of energy generation and energy efficiency.

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# Abstract

Implementation of PEDs requires immense infrastructure investments in energy efficiency measures, energy generation, transformation and storage as well as in new mobility solutions. On the other hand it is crucial to keep the social perspective of PEDs as part of the picture and to create affordable living arrangements despite the high cost of the aforementioned measures. Thus, this work aims to answer the overarching question of which infrastructure will be required to turn an existing neighbourhood into a PED using a case study with a specific district archetype. In addition, the cost of this infrastructure needs is discussed, which leads to the rather socio-psychological question of inclusion and affordability as potential barriers of PEDs. Different modelling approaches for the power, heating and cooling and mobility sectors as well as demand-side measures are applied. Those range from tailor-made mixed integer linear programming over usage of open-software to agent based modelling. After setting the basis for modelling in (Akhatova et al. 2020), with the case studies of Vienna, Nottingham, Torres Vedras and Frankfurt, some of the results and city-cases will be continued to answer the aforementioned questions about infrastructure requirements and socio-psychological barriers of implementation, by creating an archetype district taking Frankfurt Griesheim-Mitte as starting point. The results show that envelope retrofitting is crucial to fulfil the PED requirement of energy positivity and to reduce the capacities of the energy generation and storage technology. Furthermore, the PED concept can be more economical than just sticking to the status quo of importing and paying the required energy. However, the high up-front cost can be a barrier for less wealthy societies. This barrier needs to be reduced by public schemes or clever business models to avoid creating an exclusive neighbourhood concept.

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## Acronyms

**ABM** Agent-based Model

**BEV** Battery Electric Vehicle

**DHW** Domestic Hot Water

**DH** District Heating

**EV** Electric Vehicle

**LP** Linear Programming

**MILP** Mixed Integer Linear Programming

**PED** Positive Energy Districts

# 1 Introduction

The concept of Positive energy districts (PEDs) is one of the key approaches to achieve climate neutrality, whereby close-lying buildings in a district must have a positive balance of renewable energy annually. However, transition of existing districts into PEDs is hardly achievable without the district energy infrastructure undergoing major transformation (Zwickl-Bernhard and Auer 2021).[1]. According to JPI Urban Europe 2020, PEDs should find its own optimal balance between the three main functions of regional energy system - energy efficiency of the infrastructure, local renewable energy production, and energy flexibility within the district (see Figure 1).

The three elements depicted in Figure 1 are relevant to different parts of district energy infrastructure, e.g. energy efficiency is ensured by weather-proofing building envelope and decarbonising heating and cooling systems. Thereby, thermal insulation and more efficient decentralised boilers or district heating systems are crucial in colder climates, while buildings in warmer climates require insulation and ventilation to reduce cooling demand in hot summer periods. Once the energy efficiency limit is achieved, local energy supply from renewable sources, such as PV or wind, is deployed to cover the local energy demand. Finally, the flexibility of the energy system can be provided by storage technologies and emerging services, such as Battery Electric Vehicles (BEV) dynamic charging. As discussed in the D4.4 - Report on developed methodologies and models for techno-economic modelling of PEDs and the transition towards their realisation (and also summarised in Section 3.3), passive and active measures modify the current energy infrastructure.

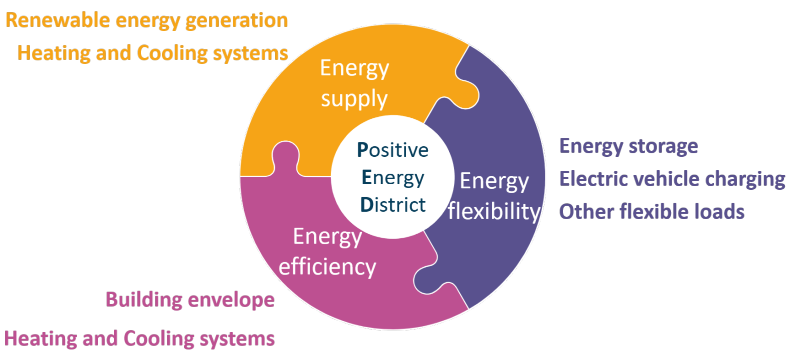


Figure 1: The key concepts/elements of Positive Energy Districts (adapted from JPI Urban Europe 2020)

Infrastructure required for an existing district to become a PED depends on many factors. Among technical factors, climate conditions (heating degree days, solar insolation, etc.) are one of the most influential ones (Bruck, Casamassima, et al. 2022). It determines how the buildings are constructed (i.e. building standards) and whether the heating or cooling supply is necessary. At the same time, demand for domestic hot water and electricity are less dependent on the climate. However, how the infrastructure develops further also depends on the systems that are already in place. For example, Denmark has an extensive network of district heating, while in the Netherlands (which has a similar climate to Denmark) gas boilers have been predominant in meeting the energy needs of the houses. Thus, while the Dutch

[1] In this report, *district's energy infrastructure* is defined as *the physical components of building and energy infrastructure systems (i.e. heating network, electricity grid) that provide commodities and services (e.g. hot water, electricity) essential to enable, sustain and enhance societal living conditions* (Fulmer 2009; Brozovsky et al. 2021)

neighbourhoods are planning to build up the district heating system, the Danish are considering how to enable the trading of heat or how to establish thermal energy communities. Due to the multitude of variables (i.e. climate, exiting systems, etc), alone in the technical domain, it is very challenging to discuss the district's infrastructure transition having a broad scale for the analysis, i.e. all European districts. Moreover, it is important to not over-narrow the system and discuss only a small part of the solution, e.g. integration and optimisation of PV and heat pumps. To the best of the authors' knowledge, there are no studies that analyse the transition of an existing district to a PED in a holistic but also techno-economically detailed way.

Due to all the dependencies of the energy infrastructure, its final planning always needs to be a case by case process. Therefore, this report aims to answer the following question:

***What is the most economical combination of energy infrastructure that is needed to transform a specifically defined district archetype into a PED?***

This is done by selecting a case study district, defining infrastructure transition scenarios and calculating the sizes of the energy supply technologies as well as the costs of each scenario. Within this study, the PED infrastructure encompasses the following technology: renewable energy generation technology, energy storage, charging technology, building envelope, district heating systems. Each technology has also parametric and installed capacity requirements. Parametric requirements refers to, for example, the supply temperature required for space heating. Finally, installed capacity indicates the size of the system, e.g. installed capacity of renewable generation technologies or the necessary capacity of the district heating generation. Such parametric and capacity requirements are usually estimated using energy models (Chang et al. 2021).

This report is structured as follows. In Section 2, the relevant literature is studied to better define infrastructure and to identify energy infrastructure important for PEDs. Section 3 presents the methodology of the work comprising of: (a) the description of the case-study (Section 3.1), (b) the definition of the transition scenarios towards PED infrastructure (Section 3.2, and (c) integrated district approach presented in D4.4 - Report on developed methodologies and models for techno-economic modelling of PEDs and the transition towards their realisation (Section 3.3). Several pathways for the transition towards a PED are presented in Section 4. Section 6 discusses the implications of the findings.

# 2 Background and literature review

This section provides an overview of how "infrastructure" and "energy infrastructure" is defined in the literature. Moreover, we determine which types of infrastructure are relevant for different PEDs and what infrastructure requirements should be considered when planning them. Finally, the interconnections between different sectors or types of infrastructure are discussed.

The term "infrastructure" is often used broadly, referring to physical structures, facilities, and networks that provide essential services to the public (e.g. water treatment and supply, transportation, healthcare infrastructure). A more practical definition of "infrastructure" based on three key things that define it: physical components, interrelation of systems and societal needs (Fulmer 2009). This means that infrastructure consists of physical components and complex and interrelated systems developed and maintained to improve social living conditions. Ultimately, energy infrastructure comprises the physical infrastructure required for producing, transforming, transmitting, distributing and storing energy (Goldthau 2014). These systems are built to provide energy services that humans need for living: heating, cooking, hygiene, etc.

When dealing with PEDs, we focus on energy infrastructure that provide fair social living conditions for occupants of residential and mixed buildings. These include residential buildings themselves and energy infrastructure that ensures the provision of energy and mobility services for a good standard of living. Energy infrastructure that is most relevant for energy services is the infrastructure involved in the provision of electricity, heating, cooling, and domestic hot water to district residents. Additionally, as we move towards decarbonisation of transportation through electrification, electric mobility also becomes an essential part of the energy infrastructure.

According to the booklet “Europe towards PEDs”, there are about 29 PED projects indicating a PED ambition and are located in 13 European countries (JPI Urban Europe 2020). These projects aim to develop new integrated strategies to achieve the urban energy system transformation, where technology plays an important role in reaching the transition. Most of the PED projects plan or have already started an implementation of an integration of a range of technologies used for generating renewable (e.g. PV, wind turbines) or secondary energy sources (e.g. waste energy), storing energy (e.g. energy storage), retrofitting of buildings (e.g. insulation, windows glazing technologies), and demand-side flexibility solutions (e.g. demand-side management platforms for balancing energy demand and supply).

Figure 2 shows that the frequently included technologies in the 29 PED projects are electric mobility (25), solar energy (22), district heating/cooling (20), heat pumps (17) and geothermal energy (15). While the most PED projects (16) consist of mixed buildings, including newly built and existing building structures, there are the 9 PED projects planning development of PEDs within only new constructed structures and the 4 PED projects plan PEDs within existing buildings. New buildings are planned to be built according to high building performance standards based on a set of procedures centred on sustainable materials, energy-efficient measures and technologies. The 6 PED projects mention that plan retrofitting of old buildings to maximise infrastructure performance.

Twenty five out of 28 PED projects mention that they include mobility in implementation strategies. While most of the projects do not provide much details of how they plan develop mobility in PEDs, it is clear that transition from conventional fossil fuel vehicles to EVs and deployment of EV charging stations for the EV adoption are the cornerstones of PED’s mobility strategies. Therefore, one of the methods proposed in this work is an assessment of accessibility of EV charging infrastructure for identifying future potential demands for EV infrastructure.

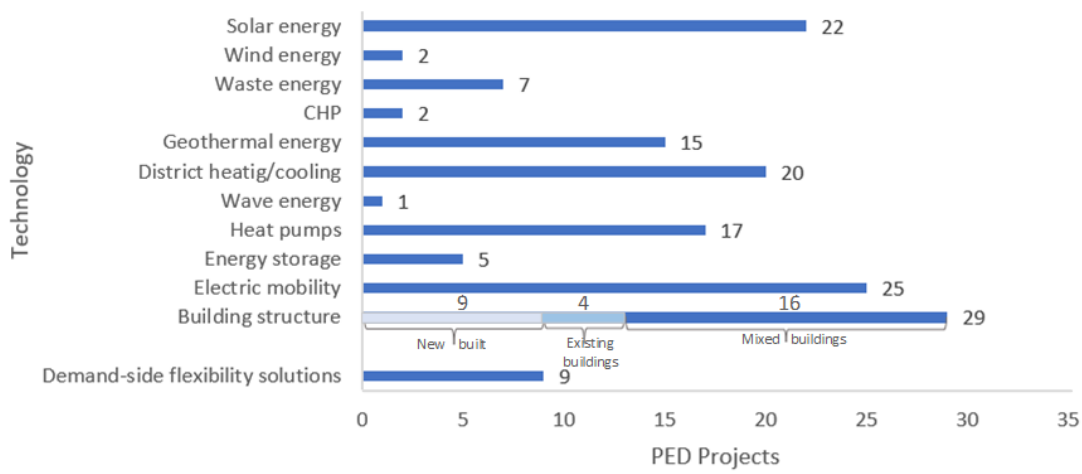


Figure 2: Technology usage among PED projects (JPI Urban Europe 2020)

As the literature on the PEDs only is not sufficient to learn about the infrastructure needs for PEDs, we draw on the peer-reviewed literature about similar to PED concepts like Zero Emission Neighbourhood and Low Carbon District (Brozovsky et al. 2021). Most of the publications about such concepts deal with various aspects of energy system (Brozovsky et al. 2021). Nevertheless, the majority of the 144 reviewed by Brozovsky et al. 2021 articles discuss the integration of multiple renewable energy sources in the energy supply system, namely planning of multi-energy systems and the management of several energy sources is the central topic of such studies (Cheng et al. 2020; Comodi et al. 2019; Capuder and Mancarella 2016; Bartolini et al. 2018; Del Pero et al. 2019; Gabaldón Moreno et al. 2021; Garau et al. 2017; Ge et al. 2019; Hachem-Vermette and Singh 2020; Heendeniya et al. 2020; Kim et al. 2019; Koutra et al. 2016; Morales González et al. 2012; Pinel, Bjarghov, et al. 2019; Pinel, Korpås, et al. 2020; Pietruschka et al. 2015). Several studies evaluate different scenarios of energy production (Zwickl-Bernhard and Auer 2021; Garau et al. 2017; Kim et al. 2019; Morales González et al. 2012; Aste et al. 2017; Niccolò Aste et al. 2020; Kılkış 2014; Rezaei et al. 2021). Few studies focus on the inclusion of thermal storage systems (Kim et al. 2019; Renaldi et al. 2017; Roccamena et al. 2019; Sameti and Haghighat 2018) and electrical storage systems (Sameti and Haghighat 2018; Shafiullah et al. 2018; Shaw-Williams et al. 2020).

A few observations can be made from the existing literature. Peer-reviewed literature either focuses on the specific aspects of the energy system (e.g. management of supply from different technologies) or discusses the non-technical aspects of PEDs, like energy justice. Hence, there is a lack of studies that contribute to the techno-economic pathway development, which is essential for policy-making. Furthermore, majority of studies are about renewable energy supply, however, energy-efficient building renovation is a very important measure that is overlooked in the studies about Positive and Net-Zero Energy/Emission concepts. There is a growing body of literature that discusses the benefits of conducting renovation at the neighbourhood or district scale (Rose et al. 2021; Paiho et al. 2019). Moreover, more studies are including the installation of PV as an active retrofitting measure (Fina et al. 2019). Hence, this study fills these gaps and contributes to a further techno-economical definition of PEDs. It does so by considering the role of building retrofitting, electric vehicle charging and district heating in defining the pathways of a district's energy infrastructure transition.

# 3 Methodology

The overall method of this work is divided into three distinct parts. Firstly, we define a common district case study which allows us to define clear system boundaries and scope necessary for techno-economic modelling (Section 3.1). The area that will serve as a case study for this report is Griesheim-Mitte, located in Frankfurt am Main. Secondly, we define scenarios for the transition of the selected district towards PED (Section 3.2). Thirdly, we apply the integrated model presented in D4.4 - Report on developed methodologies and models for techno-economic modelling of PEDs and the transition towards their realisation to analyse the defined scenarios (Section 3.3). Figure 3 summarises the three parts of the overall method.

The results of the modelling exercise allow us to discuss the impact of infrastructure transition pathways for the selected case. To be able to draw conclusions relevant for other European districts, the approach developed to compare European districts from a techno-economical perspective (Bruck, Casamassima, et al. 2022) should be considered. In the course of this work, we analyse the archetype of a district in Germany. We argue that the results of the techno-economic analysis in this area can be extended to other districts in Europe, as long as they present a similar infrastructure. It is important to point out how this method only compares districts based on technical parameters. This methodology does not consider other vital elements essential during district development (such as income distribution, cultural diversity and accessibility to services, to name a few).

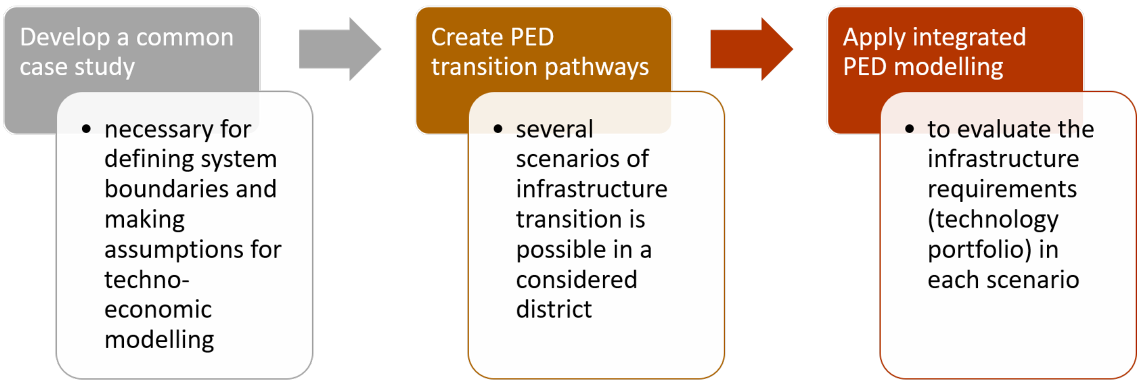


Figure 3: Methodological steps of the research

## 3.1 Common case study

f This section describes the approach used to create a common case study by district archetyping and the actual process of creating the archetype. The Smart-BEEjS project works with the partner cities of Frankfurt, Amsterdam, Vienna, Torres Vedras and Nottingham. Determining the energy infrastructure for a district in each partner city goes beyond the scope of this report. Additionally, data scarcity increases the challenge of working on each area individually. Thus, for this report we used the approach defined in (Bruck, Casamassima, et al. 2022) to create an archetype district that addresses the energy infrastructure needs of several cities. The approach uses four important parameters for energy infrastructure modelling from literature: the climate, the heat demand density, the floor space index (FSI) and the residential share of buildings. Figure 4 shows the parameters with their associated bands.

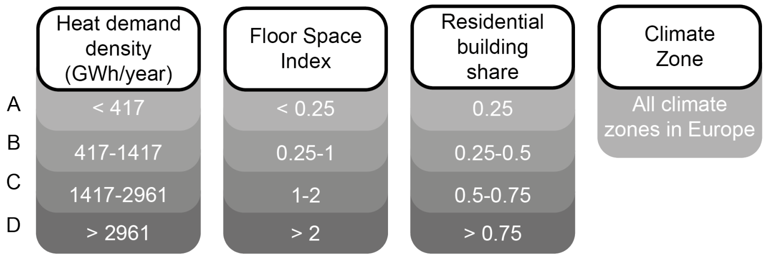


Figure 4: District categorisation matrix

Using the method described in (Bruck, Casamassima, et al. 2022) is possible to locate districts in other partner cities that are similar to each other, from a technical standpoint. The method utilises data from HotMaps (Chicherin et al. 2020) and the Köppen-Geiger classification (Kottek et al. 2006). In D4.2, the only city with a specific district to be evaluated was Frankfurt, with the district Griesheim-Mitte. Starting from Griesheim Mitte, we looked for other partner cities that fall into the same climate category, i.e. Cfb. Vienna and Torres Vedras were therefore excluded as they presented a different climate. Amsterdam and Nottingham instead lay in the same climate zone, according to the KG Classification. Utilising the developed map and its district categorisation, we found that the most similar districts in Amsterdam and Nottingham are Stadionburt and St. Ann's, respectively. A simple algorithm performs the appropriate calculation and gives a similarity score as a percentage. Appendix A explains how it determines the score. Stadionburt in Amsterdam was 84,34% similar to Griesheim Mitte, while St. Ann's scored 76,4%. Because of the similarity among the three districts, it is possible to have similar technical solutions and for the cities to draw similar conclusions about the energy transition. Stadioburt is a smaller district when compared to the other two, but this is not a problem as the results are hectare specific. Figure 5 shows the similarities between the three selected areas. As the figures shows, all districts are prevalently residential, with a low to medium-high heat demand and FSI. The districts are also primarily residential with a limited non-residential end-use.

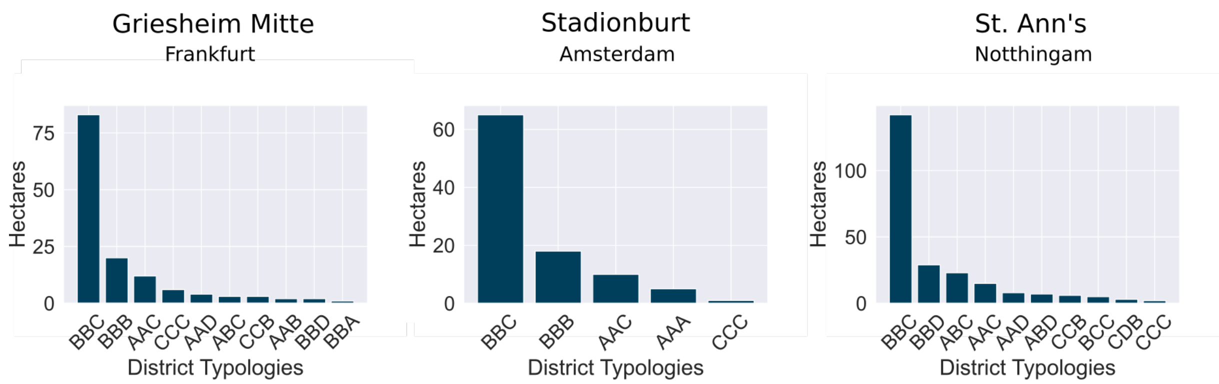


Figure 5: District typology by hectares in Griesheim Mitte, Stadionburt and St Ann's

The following sub-chapters explain this report's case study, including all data and assumptions. This case study considers solely the residential part of the district.

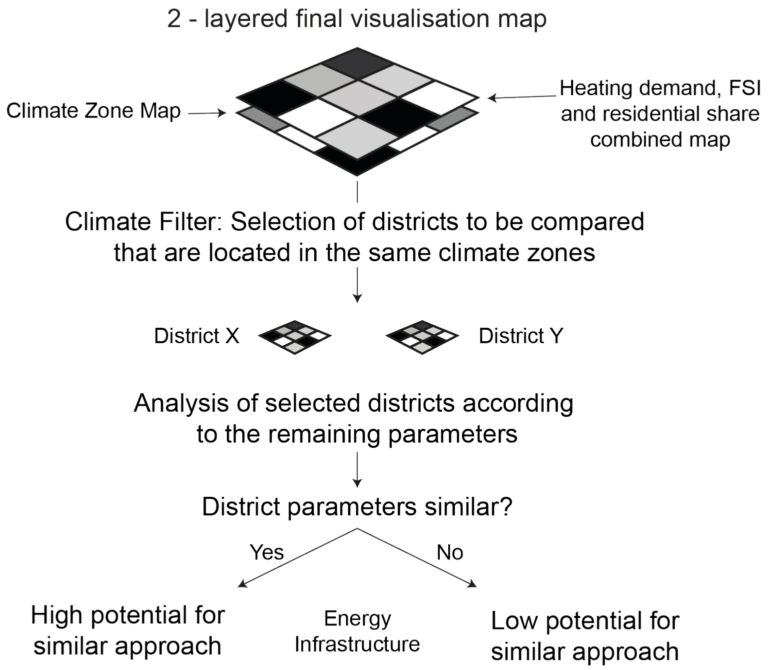


Figure 6: Archetyping approach

## *Energy demand data*

The hourly energy demand data consists of the electric load, the domestic hot water load and the space heating load. The data is taken from the synthetic load data generator synPro developed by Fraunhofer Institute (Fischer et al. 2016). SynPro provides the three loads in hourly resolution for a non-renovated multi-family building with mixed usage. The load data is scaled to match the annual residential energy demand of Griesheim Mitte. The annual demands are 4.8 GWh, 3.14 GWh and 21.4 GWh for electricity, domestic hot water and space heating, respectively. In the case of district heating an additional 10% demand is assumed due to losses in the system.

## *Meteorological data*

The meteorological data required in this study are global horizontal, direct normal and diffuse horizontal solar radiation as well as the temperature for Frankfurt in an hourly resolution. The data is taken from the ERA5 data set by the Copernicus project (Hersbach et al. 2018).

## *Spatial data*

Available space, eg. on roofs, for renewable energy generation becomes crucial in PED planning as determined in (Bruck, Santiago Díaz Ruano, et al. 2021). Table 1 shows the available space for PV panels for the case study. The area is assumed according an aerial research of Griesheim Mitte's residential buildings. For tilted roofs an angle of 30° is assumed and for flat roofs the panel points southwards and its tilt angle is equal to the one of the location's latitude.

Table 1: Roof space for PV power generation

| Azimuth angle [°] | Area [$m^2$] |
|---|---|
| 0 | 6,000 |
| 45 | 7,700 |
| 90 | 11,050 |
| 135 | 2,200 |
| 180 | 6,000 |
| 225 | 7,700 |
| 270 | 11,050 |
| 315 | 2,200 |
| Flat roof | 15,400 |

### *Cost and other assumptions*

The case study requires cost inputs, such as installation costs or energy costs per unit. The electricity cost taken for this study is 0.32 EUR/kWh, which is the average price for German households including all taxes (Eurostat 2021). For the residential cost assumptions taken for the installation and maintenance cost of the PV panels, the electricity and heat storage, the boiler and the heat pumps please refer to (Bruck, Díaz Ruano, et al. 2022; Bruck, Santiago Diaz Ruano, et al. 2022). For the industrial scale ground source heat pump, the large scale hot water storage and the electric boiler 700 EUR/kW, 15 EUR/kWh and 70 EUR/kW are assumed, respectively (Sveinbjörnsson et al. 2019; Soysal et al. 2016; Zühlsdorf et al. 2019). The carbon factor of grid-sourced electricity is 275 $gCO_2/kWh_e$ as the EU average. The renovation costs are calculated based on the cost functions by Koch et al. 2021 and refer to the costs of energy-efficient measures (insulation, waterproofing, etc).

## 3.2 PED transition pathways

Evaluation of infrastructure requirements using the integrated method described in the D4.4 report results in the capacity of cost-optimal local renewable energy in several scenarios.

In the first group of scenarios (Section 4.2.1), local renewable energy supply portfolio necessary to achieve PED is estimated without district heating (DH) and with current heat demand. It is then compared with the scenario when there is a DH (Section 4.2.2). In such case, only electricity demand is supplied by the local renewables, whereas total demand for heat and domestic hot water (DHW) in the district is assumed to be supplied by DH.

In the next group of scenarios, we estimate the new heat demand in the neighbourhood, considering the willingness of building owners to renovate their dwellings (Section 4.3). In this scenario, it is assumed that a neighbourhood-level renovation with the active engagement of an intermediary actor takes place over the course of 20 years. The updated heating demand feeds into PEDso to output the renewable energy portfolio necessary for supplying the rest of the district's energy demand. As in the scenario group without retrofitting, we evaluate two sub-scenarios: when space heating and domestic hot water is (a) supplied by individual heat pumps at each building (Section 4.3.1) and (b) distributed via district heat network based on industrial heat pump and boilers (Section 4.3.1).

The electricity demand of the increased number of public EV charging points is also calculated and the analysis of potential needs for public EV charging points for the Griesheim-Mitte is described in 4.4.

Investment costs and Net Present Values are estimated for both scenarios.

Table 2: Infrastructure transition pathways

| Scenario abbreviation | Building retrofit | Space heating and domestic hot water(DHW) | Public EV charging infrastructure |
|---|---|---|---|
| Baseline | None | Individual gas boilers | None |
| PED_noret_el | None | Heat pumps, PV, battery (fully electrified heat supply) | None / 5 public charging points with 22kW and 8 charging points with 50 kW capacity |
| PED_noret_dh | | DH supplied 100% by industrial heat pump and boilers (el) | |
| PED_socret_el | Retrofit based on building owners' preferences (i.e. social retrofitting) | Individual heat pumps | None / 5 public charging points with 22kW and 8 charging points with 50 kW capacity |
| PED_socret_dh | | DH supplied 100% by industrial heat pump and boilers (el) | |

## 3.3 Integrated PED infrastructure modelling

To evaluate the above-describe scenarios numerically, the four PED modelling approaches presented in D4.4 report are combined as shown in Figure 7.

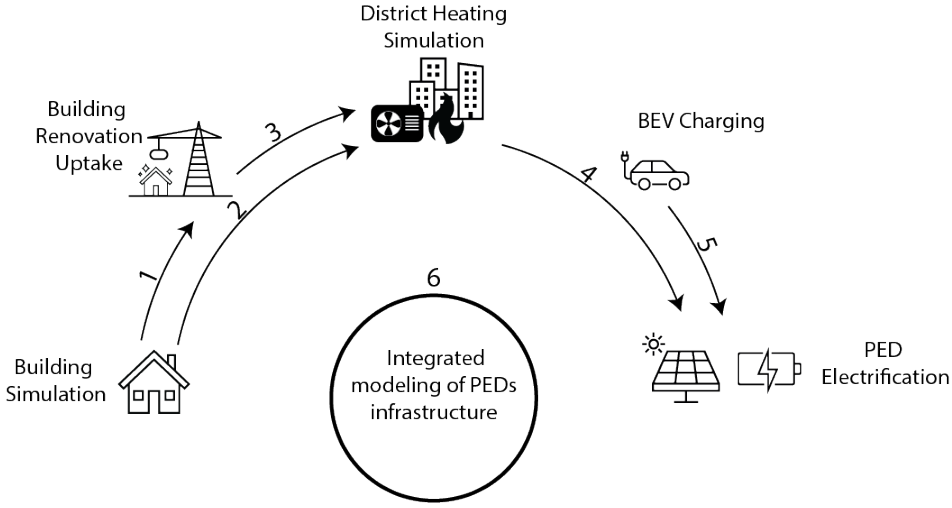


Figure 7: Integration of models and studies developed throughout the Smart-BEEjS project.

synPro is used to perform single building simulations to evaluate the energy performance and building renovation efficiency. Resulting annual specific useful space heating demand (kWh/m2/year) and the costs of retrofitting measures based on Koch et al. 2021 flow into the Agent Based Modeling (ABM) (1)

Table 3: Data inputs and outputs between the models (as depicted in Figure 7)

| Label | Input/output |
|---|---|
| 1 | Building archetypes, specific costs of retrofitting measures [EUR/m2], specific final heating demand (kWh/m2/y) |
| 2 | Total Energy Demand [kWh], Hourly Load Profiles, Internal temperature (in dwellings – Comfort Level), Specific Final Heat demand [kWh/m2/year], Cost of renovation, NPV |
| 3 | Energy efficiency measures carried out in different buildings |
| 4 | District heating demand [kWh - hourly] |
| 5 | Distribution of public EV charging infrastructure |
| 6 | Optimal energy supply technology portfolio in the district |

and the hotmaps district heating calculation (2). The specific final demand for heating and the capital costs of energy renovations are used as factors that affect the decisions of homeowner agents regarding the adoption of renovation. The ABM will provide renovation uptake as a function of time, which will provide information on which buildings can access low temperature heating as time progresses (3).

The district heating model feeds the cost for the DH grid to PEDso, which calculates the optimised electrified heating supply (4). The grid losses are set at 10% as usually suggested by the literature Vesterlund et al. n.d. Chicherin et al. 2020. Although this figure is on the lower end, as the district heating network would be built anew, it is assumed that heat losses will be minimised as much as possible. The grid installation annuity is calculated using HotMaps. In this case the total heat demand of the district is considered for the grid cost calculation. This will of course lead to an increased total cost of the district heating grid. Although in this study only the residential demand is taken into account, in reality a District Heating project will necessarily also provide heat to non residential user as they represent a more concentrated demand. Assessment of accessibility of electric vehicle charging infrastructure is applied to identify the potential future needs of charging points in Griesheim-Mitte district (5). The additional electricity demand from EV charging is used in PEDso. Finally, the PEDso consolidates the information from all the models. Locally generated PV power can be used to cover the district-wide heating demand by optimising the heat pump capacity for the entire district, alongside with the PV installed capacity and battery size to fulfill the PED requirement of having a positive energy balance. The level of retrofitting, existing and the energy demand supplied by District Heating and the number of public electric charging points determine the optimal portfolio. Hence, several scenarios pathways are determined for achieving the PED status.

# 4 Scenario results for the common case study

## 4.1 Baseline scenario

For the baseline scenario, a district that imports the entire electricity demand from the grid and satisfies the whole heating and domestic hot water demand by buring gas in gas boilers with a efficiency of 85%. The cost of electricity is assumed to be 0.32€/kWh and the cost of gas 0.1€/kWh. The resulting annual cost of solely covering the energy demand is **4,420,915€**. The emissions associated with this demand are **6,175 tonnes** of $CO_2$.

## 4.2 PED without retrofitting

### *4.2.1 Electrified heat supply (PED_noret_el)*

This scenario describes the energy infrastructure required, its associated costs and carbon emissions for the creation of a PED based on electrified heat without building envelope retrofitting. The allocated roof area for PV power generation is not sufficient to fulfill the PED criteria. Therefore, an additional area of 20,000 $m^2$ flat roof area or flat free space is allocated, since otherwise, a PED would technically not be feasible. Table 4 shows the infrastructure requirements, their cost and the grid import associated $CO_2$ emissions.

Table 4: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), Air source heat pump (ASHP), Electric Boiler (EB), and Heat Storage (HS)) and $CO_2$ emissions

| AC $[EUR]$ | PV $[kW]$ | Bat $[kWh]$ | ASHP $[kW]$ | EB $[kW]$ | HS $[m^3]$ | $CO_2$ [t] |
|---|---|---|---|---|---|---|
| 4,078,779 | 15,622 | – | 6,356 | 1,150 | 741 | 2,320 |

### *4.2.2 District heating based on industrial heat pumps (PED_noret_dh)*

This scenario describes the energy infrastructure required, its associated costs and carbon emissions for the creation of a PED based on electrified heat without building envelope retrofitting. The heat is generated, stored and distributed centralised using large scale heat pumps, boilers and hot water storage systems and a district heating network. The allocated roof area for PV power generation is not sufficient to fulfill the PED criteria. Therefore, an additional area of 15,000 $m^2$ flat roof area or flat free space is allocated, since otherwise, a PED would technically not be feasible. Table 5 shows the infrastructure requirements, their cost and the grid import associated $CO_2$ emissions, including the cost of the DH grid (AC DH: 1,110,794€). As explained in Section 3.3, the total cost of the DH Grid is calculated using HotMaps, considering the total heat demand and not only limited to the residential.

Table 5: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), Ground source heat pump (GSHP), Electric Boiler (EB), and Heat Storage (HS)) and $CO_2$ emissions

| AC $[EUR]$ | PV $[kW]$ | Bat $[kWh]$ | GSHP $[kW]$ | EB $[kW]$ | HS $[m^3]$ | $CO_2$ [t] |
|---|---|---|---|---|---|---|
| 4,630,354 | 13,805 | – | 6,888 | 657 | 975 | 1,999 |

It needs to be noticed that the total installed capacity of the large scale heat pumps is overestimated in this case. The heat demand in the district is calculated using a single load profile, which is then duplicated to meet the total annual energy demand according to ebok report. This approximation leads to all the single peak demands in the district to happen at the same time, hence the total peak becomes the sum of all single peak demands. The optimisation calculates the heat pump cost based on the total peak. In the previous scenario (i.e. Electrified Heat Supply), this is not an issue, as each single heat pump will need to cover the highest peak of the year. When large scale heat pumps are implemented this approximation becomes less precise. In reality, each building would show its peak demand at a different time of the day. This means that the sum of all the single peaks larger than the total peak of the district. In turns, this would lead to a lower total installed capacity and, as a consequence, a lower capital cost.

## 4.3 PED with neighbourhood retrofit

In this scenario, we assume that district buildings are renovated at neighbourhood level. This setup allows us to consider the group purchase (i.e. the specific cost of renovation decreases with more renovation adopters), as well as the barriers to renovation such as financial limitations of the potential renovators and their attitude towards renovation. As the data about people's attitude and its evolution are usually not available, modellers usually keep these variables stochastic and run several iterations. Hence, the results in Figure 8 (i.e. the energy saved via social retrofitting, total gross floor area renovated and the costs of renovation) are given as a range of values from 20 iterations, with median (orange line) and mean (green triangle) indicated. Apart from attitude, sources of stochasticity in this model are the weight factors and agents selected for interaction. Weight factors give a weight to financial vs environmental factor in making decision regarding the retrofit option (i.e. 5 cm to 20 cm insulation), e.g. an agent who is more environmental will try to chose a more ambitious option (i.e. thicker insulation).

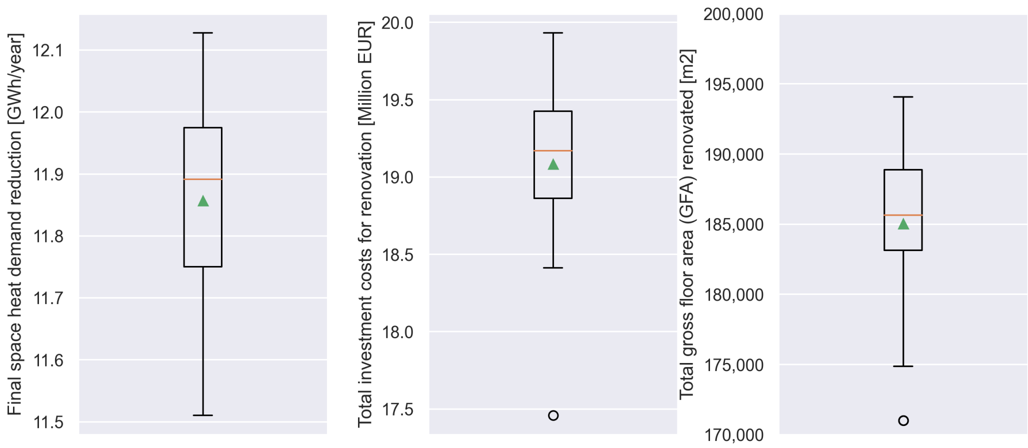


Figure 8: Boxplots of: (1) Reduction in space heat demand [GWh/year], (2) Total cost of renovation [Million EUR], (3) Total GFA of buildings renovated [m2]

Table 6 summarises the main results that are used for calculating the energy supply necessary (see Sections 4.3.1 and 4.3.2). Total costs of renovation are calculated based on the measures for improving the energy performance, such as roofing and waterproofing, thermal insulation, etc.

Table 6: Final space heating demand in the district before retrofitting ($E_0$), Gross floor area of residential buildings (in the model) $A_0$, reduction in final space heat demand ($E_{heat}$, median value), Total cost of renovation ($C_{ret}$, median value), Total GFA of buildings renovated ($A_{ret}$, median value)

| $\Delta$ $E_0$ $[GWh/year]$ | $A_0$ $[m^2]$ | $\Delta$ $E_{heat}$ $[GWh/year]$ | $C_{ret}$ $[10^6 EUR]$ | $A_{ret}$ $[m^2]$ |
|---|---|---|---|---|
| 22.4 | 202,506 | 11.9 | 19.2 | 185,643 |

Additional sub-scenarios are tested to evaluate framework conditions that are different from the one assumed for the baseline scenario. The results are shown in Table 7. More ambitious scenario represents a neighbourhood with well-connected neighbours, higher cost reduction due to group purchase and a subsidy to increase the affordability. Less ambitious scenario is the contrary of the more ambitious one and represents a neighbourhood renovation process in the neighbourhood with difficult-to-each homeowners or where the social engagement of people is not managed very well (neighbours' attitude). Input values for the parameters are listed in Table 13 in the Appendix. (see Appendix Afor more details). As seen from the results, it is possible to get the whole neighbourhood renovated, however, it will be very costly.

Table 7: Sub-scenarios, Reduction in final space heat demand ($E_{heat}$, median value), Total cost of renovation ($C_{ret}$, median value), Total GFA of buildings renovated ($A_{ret}$, median value)

| Sub-scenarios | $\Delta$ $E_{heat}$ $[GWh/year]$ | $C_{ret}$ $[10^6 EUR]$ | $A_{ret}$ $[m^2]$ |
|---|---|---|---|
| More ambitious | 16.5 | 28.6 | 202,074 |
| Less ambitious | 4.4 | 7.2 | 7,024 |

### 4.3.1 Electrified heat supply (PED_socret_el)

Using the aforementioned assumptions for social retrofitting, Table 8 shows the optimised energy technology portfolio required to turn the district in a PED with its associated cost. The annualised cost of retrofitting is included (1,051,713€).

Table 8: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), Air source heat pump (ASHP), Electric Boiler (EB), and Heat Storage (HS)) and $CO_2$ emissions

| AC $[EUR]$ | PV $[kW]$ | Bat $[kWh]$ | ASHP $[kW]$ | EB $[kW]$ | HS $[m^3]$ | $CO_2$ [t] |
|---|---|---|---|---|---|---|
| 3,668,899 | 10,365 | – | 3,021 | 1,125 | 392 | 1,556 |

### 4.3.2 District heating system based on heat pumps (PED_socret_dh)

When the building stock becomes more efficient it is possible to lower the supply temperature of heat to the buildings, although it is a general statement it also depends on the heating distribution system implemented in a house (radiators, floor heating, fan assisted, to mention a few). The lower temperature district heating is generally known as 4th Generation District Heating (GDH). Because the amount of building supplied by district heating has not changed, the trench length also stayed the same across the cases. This means the the cost of creating the trenches to lay down the pipes for district heating stayed the same acrosso cases. It needs to be mentioned that the cost of the trench varies according to the nominal diameter of the pipe (i.e. DN). HotMaps calculates an average pipe size to address the costs of digging the trenches. The 4th GDH would have larger pipes compared to older generations incurring in higher trench cost. At the same time, these same pipes would be cheaper to manufacture as they would require less insulation. HotMaps does not calculate the cost of a low temperature district heating, although it is usually argued that, due to lower thermal insulation requirements it is lower. This case scenario assumes that, overall, the cost of creating a new 4th Generation District Heating Grid is the same as a 3rd Generation. Table 9 show the optimised technology portfolio including the retrofitting cost and the cost for the district heating grid.

Table 9: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), Ground source heat pump (GSHP), Electric Boiler (EB), and Heat Storage (HS)) and $CO_2$ emissions

| AC $[EUR]$ | PV $[kW]$ | Bat $[kWh]$ | GSHP $[kW]$ | EB $[kW]$ | HS $[m^3]$ | $CO_2$ [t] |
|---|---|---|---|---|---|---|
| 4,503,130 | 9,649 | 686 | 3,246 | 1,136 | 548 | 1,337 |

As in Section 4.2.2, also here the same consideration about the total installed capacity of large scale heat pumps is valid.

## 4.4 Public EV charging infrastructure

To identify solutions for future charging infrastructure improvements in the Grieshiem-Mitte, the deployment of public EV charging points within 38 districts of the Frankfurt city have been evaluated and compared. Postcode of districts and the number of public EV charging points per district have been mapped and illustrated in Appendix A, figures 12,13. The data of the number of public charging points have been extracted from *GoogleMap* n.d. on the 18th of July 2022.

Linear regression analysis is used to understand which factors have influenced the establishment of EV charging points and how EV charging points are distributed among districts within a city. Characteristics such as population size, geographical area size, and gross floor area have been analysed at each district in accordance with the correlation with the number of public EV charging points. Due to an absence of data in terms of housing types per district in Frankfurt, gross floor area characteristic is compared among districts with similar area size, assuming that the highest number of gross floor area among districts can indicate the higher number of availability of apartment buildings. According to Soylu et al. 2016 and Hall and Lutsey 2020 housing type impacts the ability to charge at home, therefore residents for apartment buildings potentially will have higher demand for public charging than those who live in houses (e.g. detached or semi-detached) with an access to home charging. Nevertheless, gross floor area alongside with population characteristic have not show the correlation with the number of public EV charging points. Size area has show a slight correlation with the number of public EV charging points per district.

Additionally, evaluating locations of public EV charging points, it has been found that a significant number of public charging points is installed near supermarkets, commercial banks, leisure centres and large hotels. In Germany, businesses establishing charging points are partially exempted from electricity tax. Nevertheless, this policy measure has profitability only with high market penetration due to electricity tax is billed per unit of energy sold (Baumgarte et al. 2021). This means that the more profitable a location for a public charging point, the higher is the electricity tax exemption for a company installed a charger. This might be a reason of high concentration of public charging points in districts situated in the city centre with high density of commercial and entertainment buildings (ibid).

The Griesheim-Mitte district (Postcode 65933) has similar population and area sizes with the Frankfurter Berg district (Postcode 60486), Ostend (Postcode 60314) and Gallus (Postcode 60327). Nevertheless, their gross floor area characteristics are significantly lower than in the Griesheim-Mitte district. This might indicate that the Griesheim-Mitte district has more apartment buildings without an opportunity to establish a home charging than other districts. Overall, the Griesheim-Mitte district has only 3 public EV charging points, while the Frankfurter Berg, Ostend, and Gallus districts have 79, 11 and 14 charging points accordingly.

In terms of the future EV infrastructure plans in Frankfurt, *Balgaranov* 2022 state that 280 public charging points are planned to be installed in the city by 2023. Therefore, in the PED retrofit scenario, it is assumed that if the equal diffusion of charging points between districts with low or absent of availability of charging points is considered, an installation of 10 additional charging points will be required in the Grieshiem-Mitte district. Therefore, in the PED retrofit scenario the demand of 5 public slow charging points with capacity of 22kW and 8 public fast charging points with 50kW charging capacity is estimated. The EV public charging points demand profile includes three charging events per charging point per weekday and two charging events per weekend, based on Gilleran et al. 2021 study. The average delivered energy per charge point with capacity of 22kWh equaling to 5kW and duration of charging session equaling to 3 hours is applied, based on Andrenacci et al. 2022 study. Eight fast public charging points with 50kW charging capacity have been estimated with duration of charging sessions equaling to 1 hour. The weekly demand profile, averaged over full year, can be seen in Appendix A, figure 14.

Investments costs (IC) and optimised annualised cost (AC) of proposed new 2 slow (22kWh) and 8 fast (50 kWh) EV charging points are presented in Table 10. These costs have been estimated based on Mortimer et al. 2021 study where the installation, operation and utilization costs of 21,164 public and semi-public charging stations in Germany were evaluated. According to that study OPEX of slow charging point costs about 750 euro per year, OPEX of fast charging points - 1500 euro per year. Charger investment cost of 22 kW capacity costs 1,250 euro and 50 kW capacity - 15,000 euro. Therefore, annualised cost for proposed 2 slow (22kW) chargers equals to 1,885 € and for 8 fast (50kW) chargers equals to 30,567 €.

Table 10: Invetsments costs (IC) and Optimised Annualised Cost (AC) of proposed public EV chargers

| Number of chargers | Capacity of chargers $[kWh]$ | IC $[EUR]$ | OPEX $[EUR]$ | | AC $[EUR]$ |
|---|---|---|---|---|---|
| 2 | 22 | 1,250 | 750 | 1,887 | |
| 8 | 50 | 15,000 | 1,500 | 30,567 | |

# 5 Discussion

Table 11 shows the annualised costs, the district-wide emissions and where applicable the technology portfolio of the considered scenarios without the effect of EV charging. The individually electrified PED solutions are economically superior to the baseline scenario. The most economical combination for this case is individual air source heat pumps in combination with a certain retrofitting uptake. All PED scenarios drastically reduce the district-wide $CO_2$ emissions.

The district heating cases reduce the emissions slightly more than the individual heating scenarios. A centralised heating solution via large scale ground source heat pumps, electric boilers, heat storage and district heating is economically not competitive due to the very expensive DH grid. However, one has to consider that there are two effects that might boost the profitability of the DH solutions. Firstly, DH system enables the usage of waste heat from industrial or IT processes and even specific commercial activities. In the case of Griesheim-Mitte, the large data centers generate a continuous waste heat stream that could potentially be boosted and used in DH. This would reduce the required heat pump capacity and also the electricity consumption. Secondly, a district heating grid in practice reduces the total installed capacity of heat generation technology compared to individual solutions. In reality, the heat demand of individual consumers is not equal at each time step but depends on the behaviour of each individual. Thus, against the assumptions of this study, the individual heat demand peaks would not appear at the same time but would be more spread. While this would not change the individual heating solution, the capacity for heating generation equipment in the DH case would be reduced as explained in more depth in Section 4.3.1. If those effects justify a DH installation would have to be a case by case decision. Due to the assumed static electricity tariff and their expense, batteries play a minor role in the PED scenarios.

Table 11: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), Heat pump (HP) - Air/ground source (AS/GS), Electric Boiler (EB), and Heat Storage (HS)) and $CO_2$ emissions without EV charging consumption

| Scenario | AC $[EUR]$ | PV $[kW]$ | Bat $[kWh]$ | HP $[kW]$ | EB $[kW]$ | HS $[m^3]$ | $CO_2$ [t] |
|---|---|---|---|---|---|---|---|
| Baseline | 4,420,915 | – | – | – | – | – | 6,175 |
| PED_noret_el | 4,078,779 | 15,622 | – | (AS) 6,356 | 1,150 | 741 | 2,320 |
| PED_noret_dh | 4,630,354 | 13,805 | – | (GS) 6,888 | 657 | 975 | 1,999 |
| PED_socret_el | 3,668,899 | 10,365 | – | (AS) 3,021 | 1,125 | 392 | 1,556 |
| PED_socret_dh | 4,503,130 | 9,649 | 686 | (GS) 3,246 | 1,136 | 548 | 1,337 |

Figure 9 shows the comparison of the considered scenarios according to their annualised cost and its composition. Building envelope retrofitting adds significantly to the annualised cost. However, it reduces the CAPEX of energy generation and storage technology as well as the cost for electricity import even more and thus is economically feasible under the assumptions of this study. On the other hand, district heating adds an almost equal cost as retrofitting, while generating only very little cost savings in our scenarios. Therefore, a district heating system is not economically feasible under this study's assumptions.

Table 12 shows the annualised cost of all scenarios and their respective technology portfolios including the additional demand for EV charging. In all scenarios apart from the PED_noret_el scenario, the addition electricity only has a relatively small effect on the annualised cost. The cost increases slightly due

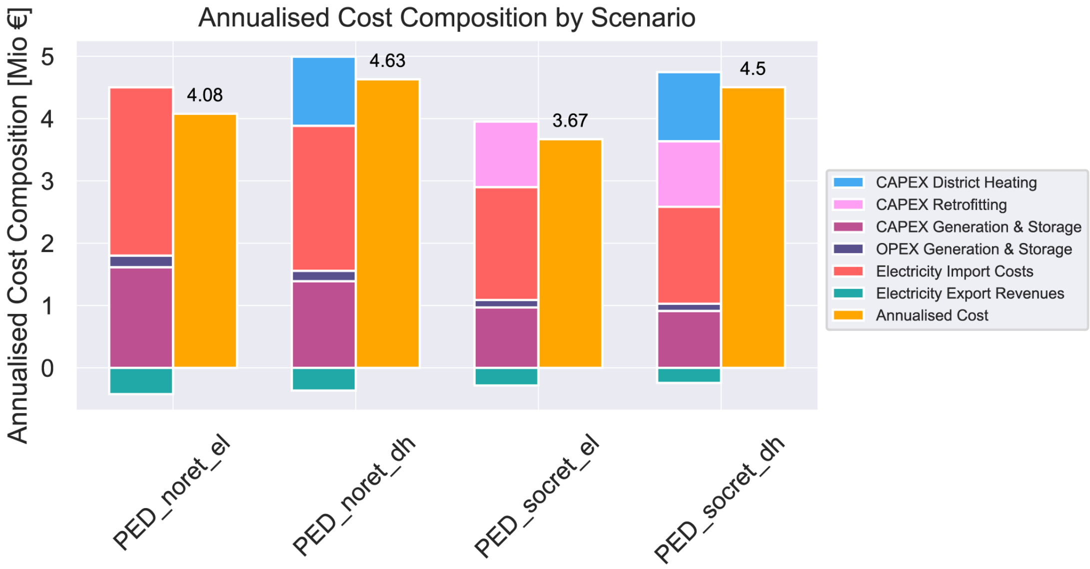


Figure 9: Comparison of the annualised cost of the PED scenarios without EV charging consumption

to the larger PV capacity required. Only in the PED_noret_el scenario the effect is larger, as the PV panel area is already maxed out. Here, the additional demand is covered by replacing the boilers with more expensive heat pumps to reduce electricity consumption elsewhere. This again shows the importance of retrofitting in ambitious district concepts such as PEDs.

Table 12: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), Heat pump (HP) - Air/ground source (AS/GS), Electric Boiler (EB), and Heat Storage (HS)) and $CO_2$ emissions with EV charging consumption

| Scenario | AC $[EUR]$ | PV $[kW]$ | Bat $[kWh]$ | HP $[kW]$ | EB $[kW]$ | HS $[m^3]$ | $CO_2$ [t] |
|---|---|---|---|---|---|---|---|
| PED_noret_el | 4,828,542 | 15,622 | – | (AS) 9,999 | – | 3,769 | 2,309 |
| PED_noret_dh | 4,747,584 | 14,541 | – | (GS) 6,888 | 645 | 975 | 2,062 |
| PED_socret_el | 3,786,049 | 11,145 | 53 | (AS) 3,021 | 1,123 | 391 | 1,614 |
| PED_socret_dh | 4,615,088 | 10,053 | 588 | (GS) 3,269 | 594 | 511 | 1,431 |

# 6 Conclusion

The infrastructure requirements for PEDs depend on many factors, including climate conditions and settlement's density (i.e. energy density). Thus, planning of PEDs needs to be contemplated on a case-specific basis. This work discusses some possibilities of transforming an existing district archetype into a PED. The archetype is based on the neighbourhood of Griesheim-Mitte in Frankfurt. Nevertheless, the results of the analysis on Griesheim-Mitte is also relevant for the districts in Amsterdam or Nottingham due to high similarity according to (Bruck, Casamassima, et al. 2022).

The analysis shows that for the specific district archetype, building envelope retrofitting plays a substantial role. As in urban areas, space is frequently a limiting but at the same time decisive factor for installation renewable energy generation sites, a lack of building retrofitting could significantly impact meeting sufficient energy demand in PEDs. As renewable energies employed in an urban environment usually have a low energy density, space can become a limiting factor. Hence, it becomes necessary to drastically reduce the energy demand in the first place, to be able to cover the demand within the available space. This is especially true when electrifying the heating sector. As seen in the modelling results, the optimisation model could not find an economically viable solution without renovations as the space available for PV installation was too small. Nevertheless, despite JPI Urban Europe 2020 stating the importance of energy efficiency, building retrofitting falls behind in the current list of undergoing PED projects, as shown in Figure 2. Thus, it is extremely important to increase the energy efficiency in existing districts at a faster pace, if we aim to meet the 3% building renovation rate goal, as well as the deployment of smarter energy management. These two solutions combined are the cornerstone of Positive Energy Districts.

Further findings indicate that individual heat pump solutions are more economical compared to a centralised approach with a district heating network. However, certain positive effects of district heating grids, such as the ability to use industrial waste heat, are not assessed. In general, PV generation plays a large role in all PED scenarios, as well as thermal or electric energy storage. Due to the static tariff chosen for this study, expensive batteries are less important.

One important limiting factor of PEDs is the high upfront investment cost, even though the PED concept is often more economical than the status quo over the whole project lifetime. As inclusion and affordability are one of the aspects of the PED concept, it is important to ensure that PEDs are an economically viable solution in the long term. The high upfront investment cost of energy infrastructure could be addressed through applications of public schemes and innovative business models, allowing the participation of the different socioeconomic classes of population. These considerations are true even when we do not include the costs of health care related to polluted air, poor housing conditions and cold environments, to mention a few.

PED increases energy autonomy by decreasing the need of importing electricity from other areas or raw materials and has the potential of redistributing the energy generation across the population, rather than concentrating it in specific areas. This redistribution not only has positive repercussions on the distributive justice, but also allows the local population to manage their energy flows. This study also analyses the geographical distribution and capacity charging of public EV charging in the considered district. The study found discrepancy between availability of charging points among districts and offer the number of chargers that can be added to the Griesheim-Mitte district in order to provide equal access to public EV charging infrastructure and being on track towards a fair energy transition. Although this study has focused on Frankfurt city and specifically the Griesheim-Mitte district, the applied method can be a useful tool for other cities and districts in Europe aiming to identify a more geographically and socially equal distribution of public EV charging infrastructure.

The results of this study are limited in various ways. Firstly, only one case study is assessed. The results might be completely different for an extremely southern or northern district archetype. Furthermore, the applied methodologies to obtain the results are only one out of many pathways to obtain the infrastructure requirements for PEDs. This study only focuses on spatially bound districts and do not consider those that could distribute energy generation beyond the district borders. Also, the waste heat from data centers in Griesheim-Mitte district is not taken into account in the assessment, which is a central point of 4th Generation District Heating systems. With EV infrastructure, only public charging infrastructure has been included in the modelling. Finally, this study is limited to a certain set of technologies, which could be extended in future works.

In future studies, exploration of the infrastructure requirements for PED transition in other district archetypes is suggested to gain a more complete image of PED feasibility across Europe's climates and different end user patterns. Furthermore, a study of PEDs that can supply energy generation beyond the district borders could be in the interest for future research. This would open further technology options such as wind power. On the other hand, possible negative effects on the power grid would need to be discussed and compared to spatially closed districts. Further effort is needed regarding the time factor. This study addressed the status quo and a possible ideal scenario, in which buildings have undergone renovations. It is important to understand how the infrastructure can develop over time analysing also middle steps. The agent-based model presented in this report can output the amount of renovations performed at defined time-steps (e.g every six months). Hence it would be possible, in the future, to analyse how to optimise the infrastructure including these middle steps and how the cost would change when more buildings undergo renovations.

# A Appendix

## Two extra scenarios for ABM

Table 13: Parameters of the Agent-based Model

| | **(1) More ambitious/-positive scenario** | **(2) Less ambitious/ positive scenario** | **Explanation of the variables and the impact** |
|---|---|---|---|
| ***Uncertainty due to the presence of intermediary*** | ***Reduced*** | ***Increased*** | |
| opinion_threshold | -0,7 | 0,3 | With lower opinion thresholds, agents with more negative attitude to start considering retrofitting; when the opinion threshold is higher, only positively inclined agents consider renovation |
| ***Connectedness and interaction in the neighbourhood*** | ***Well-connected and sociable neighbours*** | ***Less well-connected and less sociable neighbours*** | |
| mu | 0,5 | 0,1 | mu is the parameter that decides how strongly an agent is influenced by somebody else's opinion upon random interaction. Same for all agents. |
| gamma | 0,3 | 0,1 | gamma is the parameter that decides how strongly an agent's opinion has changed after agreeing to retrofit (i.e. adoption). Same for all agents. |
| number of interacting agents | 4 | 1 | |
| ***Specific cost reduction due to group purchase*** | ***Higher*** | ***Lower*** | |
| group factor | 0,05 | 0,01 | group factor is the parameter that decides how strongly the costs reduce (i.e. it controls the slope of a log curve). Higher group factor means that costs reduce more drastically depending on the number of buildings agreeing to renovate |
| ***Subsidies*** | ***Higher subsidies*** | ***Lower subsidies*** | |
| subsidy | 5000 | 0 | Subsidy for agents (EUR/agent) increases the affordability of the renovation options. Same amount for everybody. |

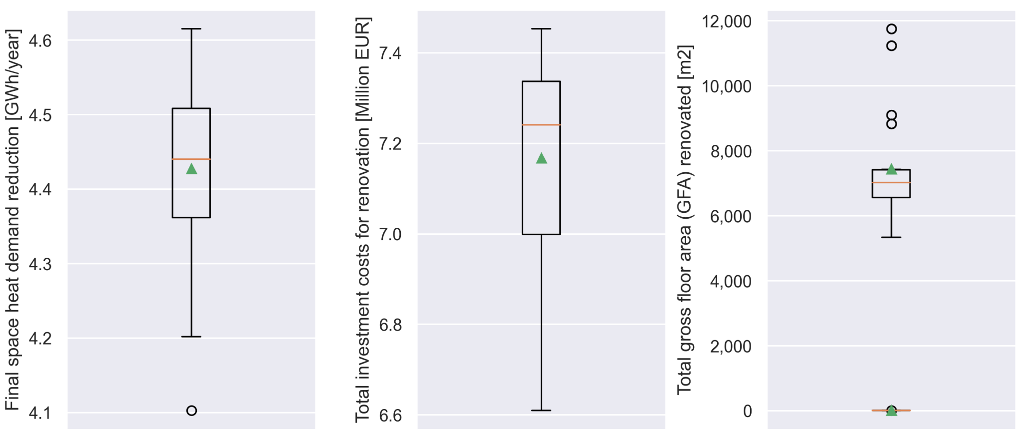


Figure 10: Boxplots of: (1) Reduction in space heat demand [GWh/year], (2) Total cost of renovation [Million EUR], (3) Total GFA of buildings renovated [m2]

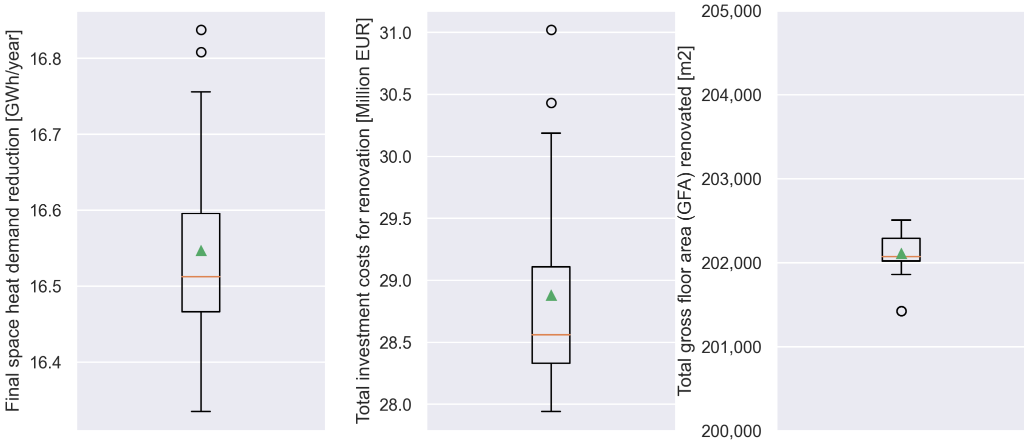


Figure 11: Boxplots of: (1) Reduction in space heat demand [GWh/year], (2) Total cost of renovation [Million EUR], (3) Total GFA of buildings renovated [m2]

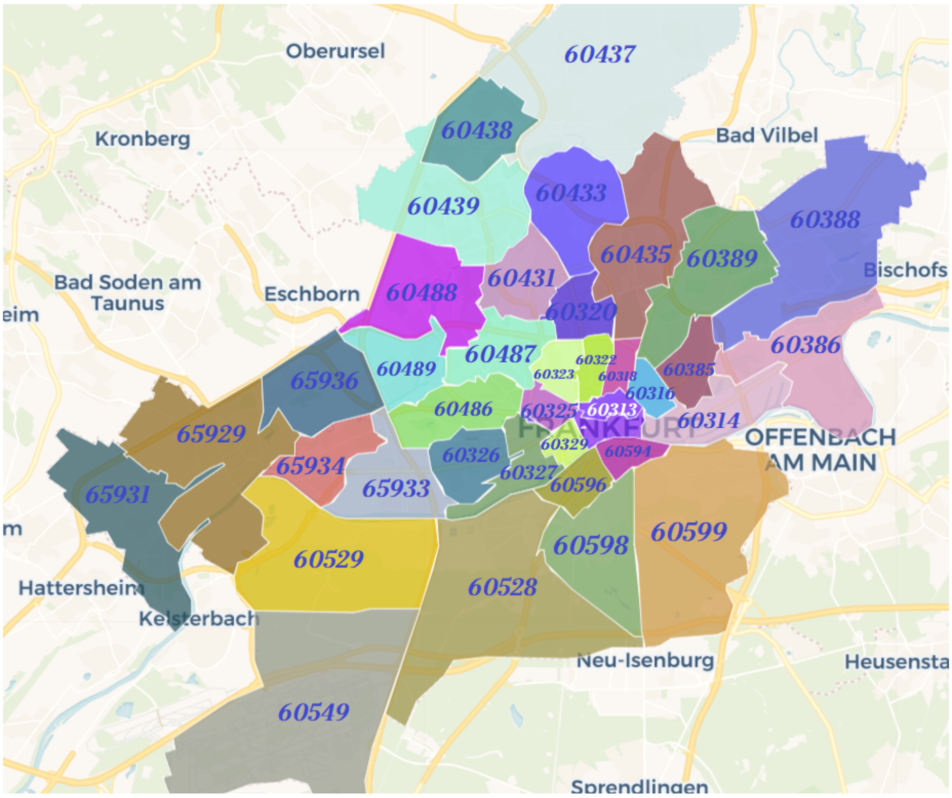


Figure 12: Frankfurt's districts

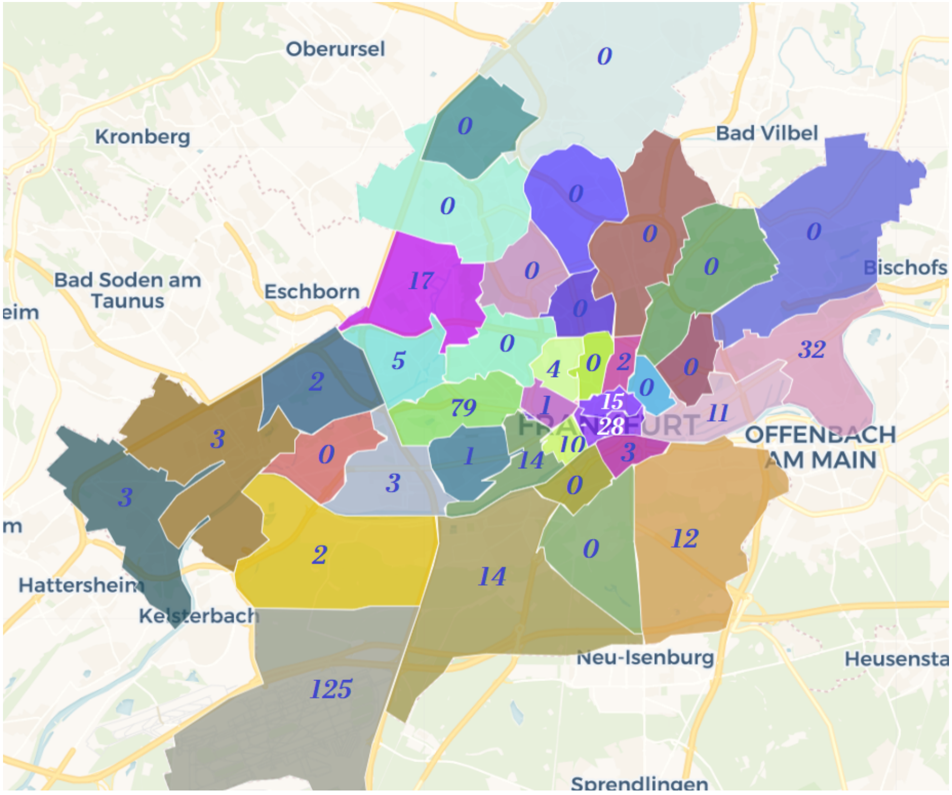


Figure 13: Numbers of public EV charging points per district.

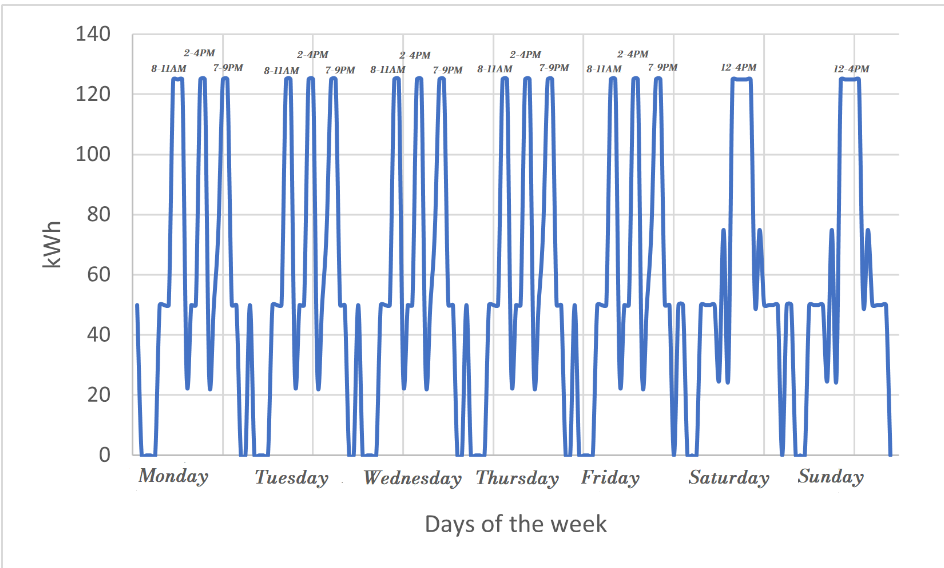


Figure 14: Weekly demand profile, averaged over full year, for 5 slow and 8 fast public charging points with 3 charging sessions per charger per weekday and 2 charging sessions per weekend with average charging duration - 3 hours for slow public charging and about 1 hour for fast charging

## Comparison Algorithm

This section explains the process to select the most appropriate district in a city when comparing it to another. For this work, we utilised an open-source software called QGIS. QGIS allows performing several different types of geographical analysis on raster files. First of all it is necessary to download the open-source raster created in Bruck, Casamassima, et al. 2022 at the GitLab repository. The raster at the previous link covers the virtually all cities in Europe. After importing the raster in QGIS (or any other GIS software), the user should also import a shapefile with all the districts in the city. Usually these files are provided by the local municipality and are relatively easy to locate on the internet. A shapefile is a generic file which delineates areas in the form of a line or a solid shape. If the shapefile is provided as layer with several attributes, we suggest to first split the layer, possibly based on an easily trackable identifier. Once the two file are imported (the raster file and the shapefile), the user should head to the top drop-menu and select Raster, Extraction, Clip Raster by Mask Layer. In this case the mask layer is the shapefile with all the single districts available in a given city. The input layer is the raster layer. As many cities might have many districts, we suggest to utilise the option "Run as a batch process" to speed up the process. At this point the user will have generated several raster layers, each one for each of the district in the city.

To compare a district to any other given district in another city, this study relied on a python script, rather than visual inspection. Although vision inspection can be very useful to quickly identify similar areas, for this work we decided it was more reliable and replicable to utilise an objective method. The code is listed at the end of this section. The code sums up all the single cell in the raster (in this specific case a cell is equal to a hectare) and categorise them by their typology (for example BBC or AAB, to mention a few). Because the districts will have different sizes, the code also calculate the percentage of a district type over the total hectares. The code then proceeds to compare the two districts. In order to do so, it assesses whether a certain district type is present in both or not (function called "compare" in the code). If both districts have a specific district type, the algorithm stores the lowest of the two values. The sum of all lowest common values is the percentage score utilised in this study.

Appendix B shows the code with relevant comment to understand the flow and the functions utilised.

# B Appendix

```
"""
Created on Wed Jul 20 11:02:31 2022

@author: Luca Casamassima
"""
import os
import imageio
import numpy as np
import pandas as pd

#path to raster files with tif extension
path = "Districts_tiffs"

files = os.listdir(path)
districts = []
j = 0

#import all raster files from folder specified in Path as a list

for i in files:
    districts.append(imageio.imread(path+"/"+files[j]))
    j += 1


#cleaning the files from clutter and making
#it easier to process later
j = 0
for i in districts:

    districts[j] = np.asarray(districts[j])   #convert tifs to arrays

    districts[j] = districts[j][districts[j]>0.0000001] #get rid of
                                                         #values that
                                                         are nearly zero
    districts[j] = districts[j].flatten() #convert to a list
    j +=1

#convert the list of districts in a Pandas Data Frame
df = pd.DataFrame(index = ["Unique_values", "Total_Sum", \
"Percent_on_total","Sum_shared", "Indiv_share" ], columns = files)


#each number in the list districts is an hectare on the map with
```

```
#a district type code the following function counts how many
#time a district type occurs and generates a dict
#that contains the code and number of occurrencies
# i.e. how many hectares are present of a given district type

def unique(value):
    """
    generates a dictionary with a list of district typology codes
    and their related amount in hectares
    as a dictionary

    """
    u_value, c_value = np.unique(value, return_counts= True)
    value_dict = dict(zip(u_value, c_value))
    return value_dict

#applying the previous function to all the districts in the city
#and calculating the total hectares in the districts
j= 0
for i in df.columns:
    df[i]["Unique_values"] = unique(districts[j])
    df[i]["Total_Sum"] = sum(df[i]["Unique_values"].values())
    j +=1

#we need to calculate the percentage each hectare type for each district
#first we fill in the correct Data frame row with a copy of Percent_total
#they will have the same length

j = 0
for i in df.columns:
    df[i]["Percent_on_total"] = df[i]["Unique_values"].copy()

#now we perform the actual calculation.
#the percentage on the total is a dictionary that says the ratio of each
#hectare type compared to the total hectares in the district
for i in df.columns:
    print(i)
    for h in df[i]["Unique_values"]:
        df[i]["Percent_on_total"][h] = \
        df[i]["Unique_values"][h]/df[i]["Total_Sum"]

#creating the function to perform the comparison
#between all districts in the city
#with another given one (in our case Griesheim Mitte)
def compare(x,y):
    shared = {}
```

```
    for i in x.keys():
        if i in y.keys():
            shared[i] = min(x[i], y[i])
    return sum(shared.values()), shared

#importing and doing all the same stuff to the case of Griesheim Mitte
gm = imageio.imread('griesheim_analysis.tif')
array_gm = np.asarray(gm)
clean_gm = array_gm[array_gm > 0.000001]
flat_gm = clean_gm.flatten()
gm = flat_gm
u_gm, c_gm = np.unique(gm, return_counts=True)
gm_dict = dict(zip(u_gm, c_gm))
tot_gm = sum(gm_dict.values())
per_gm = gm_dict.copy()

for i in per_gm.keys():
    per_gm[i] = per_gm[i]/(tot_gm)

#now we apply the "compare" function to all districts in the city and GM
for i in df.columns:
    df[i]["Sum_shared"], df[i]["Indiv_share"] = \
    compare(df[i]["Percent_on_total"], per_gm)

by_similarity = df.sort_values(by="Sum_shared", axis=1, \
ascending=False, inplace=False, kind="quicksort", na_position="last")
```

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