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

Bruck, Axel[1,2]; Casamassima, Luca[2]; Akhatova, Ardak[2]; Arslangulova, Botakoz[3]; Kranzl, Lukas[2]; Galanakis, Kostas[3]

[1] Instituto Tecnológico de Canarias, Departamento Energías Renovables; [2] Energy Economics Group, Technische Universität Wien; [3] Nottingham Trent University

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Actions, Innovative Training Networks, Grant Agreement No 812730.

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.

Document Information

Grant Agreement: 812730
Project Title: Human-Centric Energy Districts: Smart Value Generation by Building Efficiency and Energy Justice for Sustainable Living
Project Acronym: Smart-BEEjS
Project Start Date: 01 April 2019
Related Work Package: 4
Related Task(s): 4.2
Lead Organisation(s): Nottingham Trent University; TU Vienna
Editor(s): Kranzl, Lukas, Galanakis, Kostas
Submission Date: 30 September 2022
Dissemination Level: Public

Modification History

Date	Submitted by	Reviewed by	Version
30-09-2022	Kostas Galanakis	the Editors	v1.0

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 create affordable living arrangements despite the high costs 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. As existing districts in Europe are highly heterogeneous and, thus, difficult to analyse, this study uses a case study with a specific district archetype. To address this issue, thist study utilises the district comparability tool, a framework created as part of the SMART-BEEjS project to enable technical comparability across distircts in Europe.In addition, the cost of the necessary infrastructure is estimated, which leads to the discussion of inclusion and affordability issues as potential barriers of PEDs.

An integrated techno-economic modelling consisting of different modelling approaches for the power, heating and cooling and mobility sectors as well as demand-side measures are applied. Those include tailor-made mixed integer linear programming, synPro simulations, agent based modelling and statistical correlations. Using these modelling methods, several plausible transition scenarios are analysed based on the building, climate and socio-demographic data of an archetype district of Griesheim-Mitte in Frankfurt am Main (Germany).

The results show that envelope retrofitting is crucial to fulfill 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 the business-as-usual scenario of importing the required energy. However, high upfront costs can be a barrier for less wealthy societies. This barrier needs to be reduced by public schemes or smart business models to avoid creating a neighbourhood concept that does not uphold the principles of energy justice and inclusion.

This study has its limitations in terms of the scope of the study. Only one district archetype (based on Griesheim-Mitte in Frankfurt am Main and relevant for districts in Nottingham and Amsterdam) is analysed. Further work could look into different archetypes and the transition scenarios for those. Moreover, not all scenarios, i.e. transition measures could be modelled quantitatively within the frame of this work. In particular, the waste heat from data centers in the selected district was not considered. Hence, applying industrial waste heat for powering district heat networks should be investigated more thoroughly in the future.

Table of Contents

List of Figures

List of Tables

Acronyms

4th GDH	4th Generation District Heating
ABM	Agent-based Model
AC	Annualised Costs
BEV	Battery Electric Vehicle
DHW	Domestic Hot Water
DH	District Heating
EV	Electric Vehicle
FSI	Floor Space Index
IC	Investment Costs
KG	Köppen-Geiger
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 improving the 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.

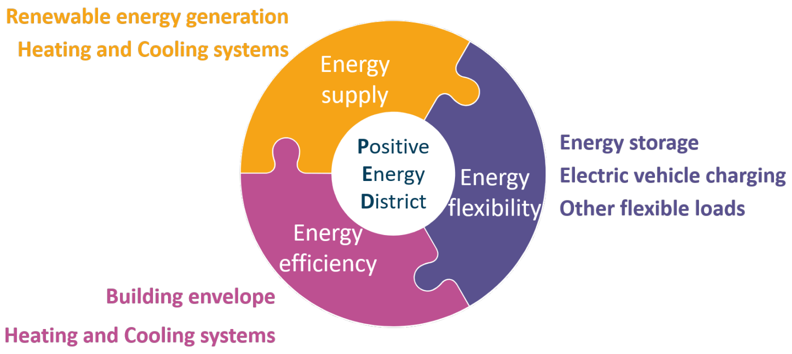


Figure 1: The key concepts/elements of Positive Energy Districts (adapted from JPI Urban Europe 2020)

The 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) individual gas boilers have been predominant in meeting the energy needs of

---

[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)

the houses. Due to the multitude of variables (climate, exiting systems, building stock condition, to name a few), alone in the technical domain, it is very challenging to discuss the district's infrastructure transition having a broad geographical scale for the analysis, e.g. 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 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 5 compares the scenarios results and discusses the implications of the findings. Finally, 6 sums up this study, by highlighting the limitations of the work and the directions for future work.

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" defines it as based on three main elements: physical components, systems interrelation 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. The energy infrastructure that is most relevant for energy services is the one 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). 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 its related charging infrastructure 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.

While most PED projects (16) consist of mixed buildings, including newly built and existing building structures, there are 9 PED projects plans based exclusively on newly developed structures and 4 projects with 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. A total of 6 PED projects, shared between mixed and exclusively existing buildings, explicitly plan energy retrofits to maximise performance.

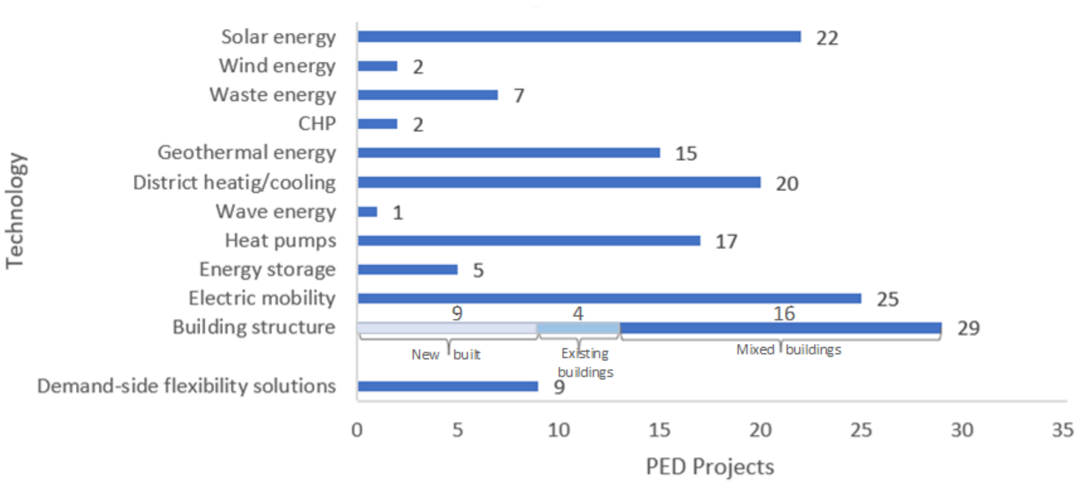


Figure 2: Technology usage among PED projects (JPI Urban Europe 2020)

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 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 publications reviewed by Brozovsky et al. 2021 discuss the integration of multiple renewable energy sources in the energy supply system. Planning 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 Positive and Net-Zero Energy/Emission concepts studies. 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 delineate clear system boundaries and scope necessary for techno-economic modelling (Section 3.1). The area that serves 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).

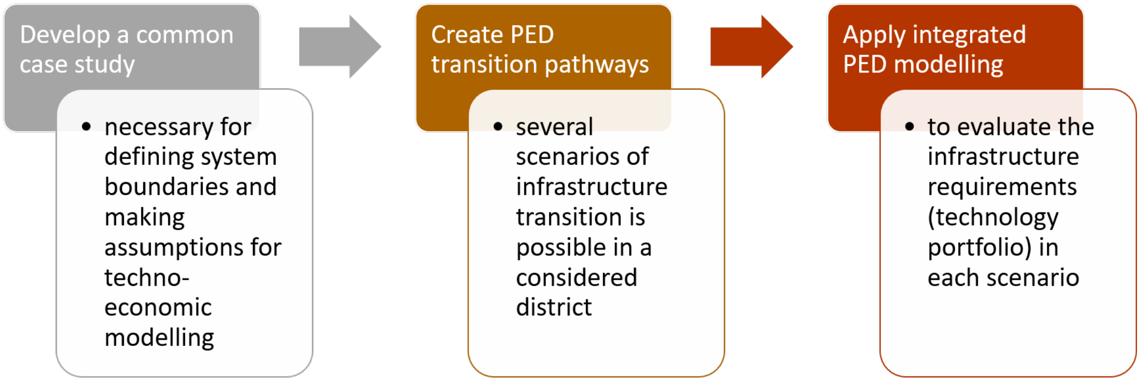
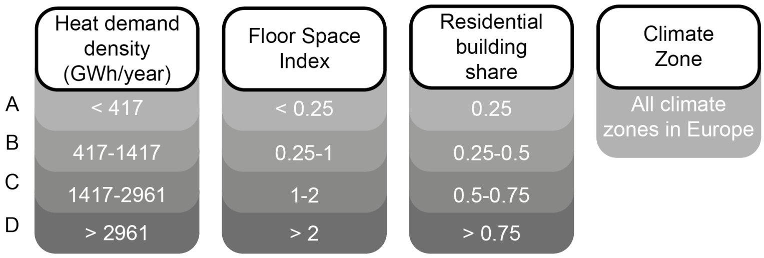


Figure 3: Methodological steps of the research

3.1 Common case study

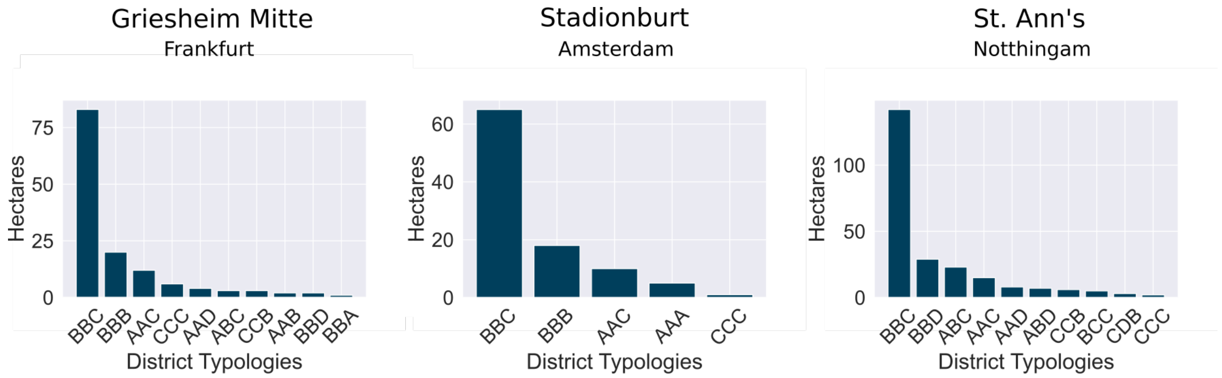
This section describes the approach of coming up with a common case study by creating a district archetype. The Smart-BEEjS project works with the partner cities of Frankfurt, Amsterdam, Vienna, Torres Vedras and Nottingham. Determining the energy infrastructure for districts in each partner city goes 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.



	Heat demand density (GWh/year)	Floor Space Index	Residential building share	Climate Zone
A	< 417	< 0.25	0.25	All climate zones in Europe
B	417-1417	0.25-1	0.25-0.5	
C	1417-2961	1-2	0.5-0.75	
D	> 2961	> 2	> 0.75	

Figure 4: District categorisation matrix

Using the method described in (Bruck, Casamassima, et al. 2022) it is possible to locate districts in other partner cities that are similar to each other from a technical standpoint. The method utilises heat demand density data from HotMaps (Chicherin et al. 2020) and the Köppen-Geiger (KG) classification (Kottek et al. 2006). In Akhatova et al. 2020, 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 are 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 Stadionbuurt 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. Stadionbuurt 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. Stadionbuurt 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 show, all districts are predominantly residential, with a low to medium-high heat demand and FSI. The districts are also primarily residential with a limited non-residential end-use.



Griesheim Mitte
Frankfurt

Stadionburt
Amsterdam

St. Ann's
Notthingam

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.

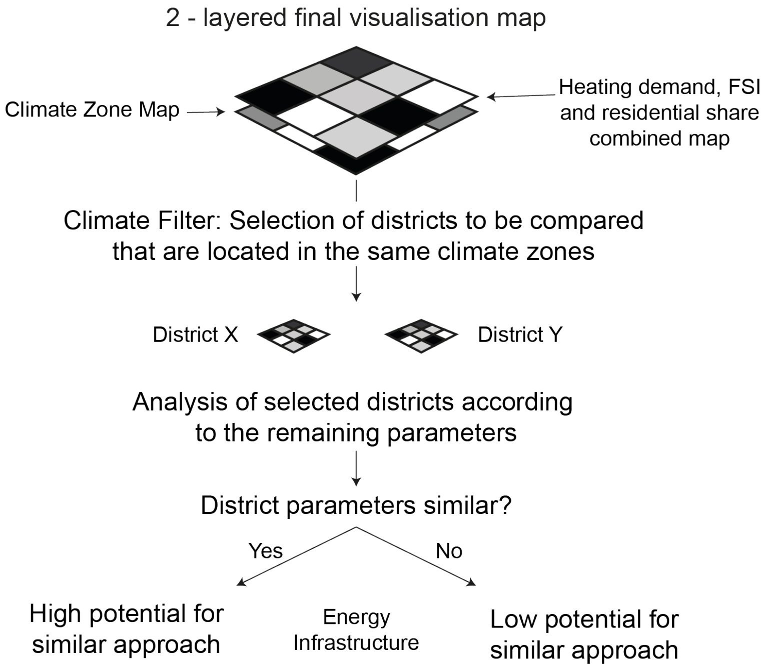


Figure 6: Archetyping approach

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, e.g. 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; oysal 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, local renewable generation supplies both the buildings' electricity demand and the electricity needed for heat and domestic hot water (DHW) generation distributed through a district heating grid 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 Section

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.

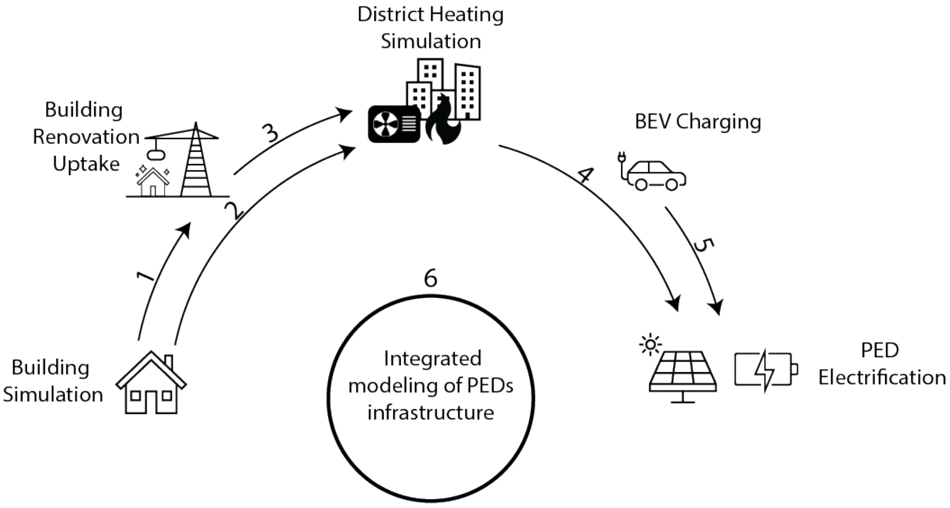


Figure 7: Integration of models and studies developed throughout the Smart-BEEjS project.

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 (Chicherin et al. 2020; Vesterlund et al. n.d.). 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 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 also provide heat to non-residential users 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 model 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 EV charging points determine the optimal portfolio.

4 Scenario results for the common case study

4.1 Baseline scenario

The baseline scenario, assumes that the district imports the entire electricity demand from the grid and satisfies the whole heating and domestic hot water demand with gas boilers with a efficiency of 85%. Based on the current statistical developments (2021 - 2nd semester), the cost of electricity is assumed to be 0.32€/kWh (Eurostat 2022) and the cost of gas 0.1€/kWh (Deutschland 2022). 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 of a PED based on heat supply via a DH network supplied by industrial heat pumps (without building envelope retrofitting as in 4.2.1). The heat is generated, stored and distributed centrally 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 not be technically 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 which is not only limited to the residential one.

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

The total installed capacity of the large scale heat pumps is overestimated in these calculations. 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 the report Main 2019. This approximation leads to all 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 4.2.1, 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 is larger than the total peak of the district. In turn, this would lead to a lower total installed capacity and, as a consequence, to a lower capital cost.

4.3 PED with neighbourhood retrofit

In this scenario, we assume that district buildings are renovated at a 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. The shares of median heat demand reduction (53%) and gross floor area renovated (92%) over total are provided in the graph as well. 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).

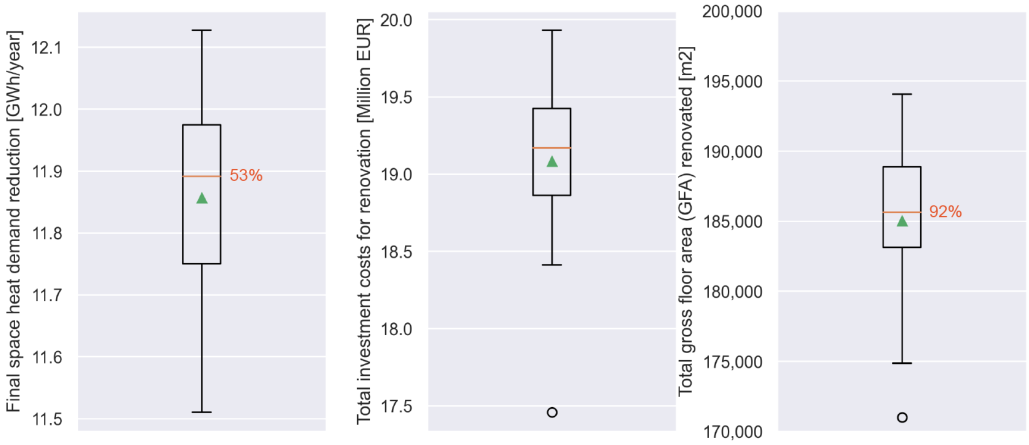


Figure 8: Boxplots of: (1) Reduction in space heat demand [GWh/year], (2) Total cost of renovation [Million EUR], (3) Total GFA of buildings renovated [m2] (median values are indicated as percentage of the initial values).

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)

Δ E_0 [$GWh/year$]	A_0 [m^2]	Δ 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	Δ 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 presents the optimised energy technology portfolio and the costs associated with transforming the district into a PED. 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 individual 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 number of buildings 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 across 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 Griesheim-Mitte, the deployment of public EV charging points within 38 districts of the Frankfurt city have been evaluated and compared. The 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. 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. However, due to an absence of data on housing types per district in Frankfurt, gross floor area is compared among districts that have a similar area within the city, assuming that the highest number of gross floor area among districts can indicate the higher number of apartment buildings. Nevertheless, gross floor area alongside with population size have not shown the correlation with the number of public EV charging points. Area size has shown 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 is profitable only with markets with a high EV penetration as the electricity tax is billed per unit of energy sold ((Baumgarte et al. 2021). This means that the more profitable a location is 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 (Baumgarte et al. 2021).

The district of Griesheim-Mitte (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 Griesheim-Mitte. This might indicate that Griesheim-Mitte has more apartment buildings without an opportunity to establish a home charging than other districts. Overall, Griesheim-Mitte has only 3 public EV charging points, while Frankfurter Berg, Ostend, and Gallus 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, it is assumed, that the new public charging points would be equally redistributed between districts with a low availability or complete absence of charging points, thus an installation of 10 additional charging station is suggested in Griesheim-Mitte. Therefore, in the PED retrofit scenario, the hourly demand profile of the 5 public slow charging points (3 existing and 2 more suggested) with capacity of 22kW and 8 public fast charging points with 50kW charging capacity are 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. The average energy delivered by charge points with the capacity of 22 kW is 15kWh over 3 hours charging period, based on Andrenacci et al. 2022. The eight fast public charging points with 50kW charging capacity have been estimated to have 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 two new slow (22 kW) and eight fast (50 kW) EV charging points are presented in Table 10. These costs have been estimated based on Mortimer et al. 2021, which evaluated the installation, operation and utilization costs of 21,164 public and semi-public charging stations in Germany. According to that study, the OPEX of slow charging point costs about 750 EUR per year, while fast charging points costs 1500 EUR per year. The investment cost of a 22 kW charger amounts to 1,250 EUR, a 50 kW charger amounts to 15,000 EUR. Therefore, the annualised costs over 8 years, with a 5% discount rate for the proposed two slow chargers (22kW) equals 1,885 EUR and for 8 fast (50kW) chargers equals 30,567 EUR.

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

Number of chargers	Capacity of chargers $[kW]$	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 retrofitting. 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 enhance 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.

Another factor that could improve the profitability of a DH scenario is that a DH grid in practice reduces the total installed capacity of heat generation technology compared to the 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. This contemporaneity effect, together with the presence of usable waste heat, might justify a DH installation, but this has to be a case by case decision. Due to the assumed static electricity tariff and their expenses, batteries play a minor role in the PED scenarios, as the profit will not change between low demand and peak times.

Table 11: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), Heat pump (HP) - Air/ground source (AS/GS), Electric including 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 costs (AC) and its composition. Building envelope retrofitting adds significantly to the total annualised cost. However, it reduces the CAPEX of energy generation and storage technology. Retrofitting reduces the costs 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.

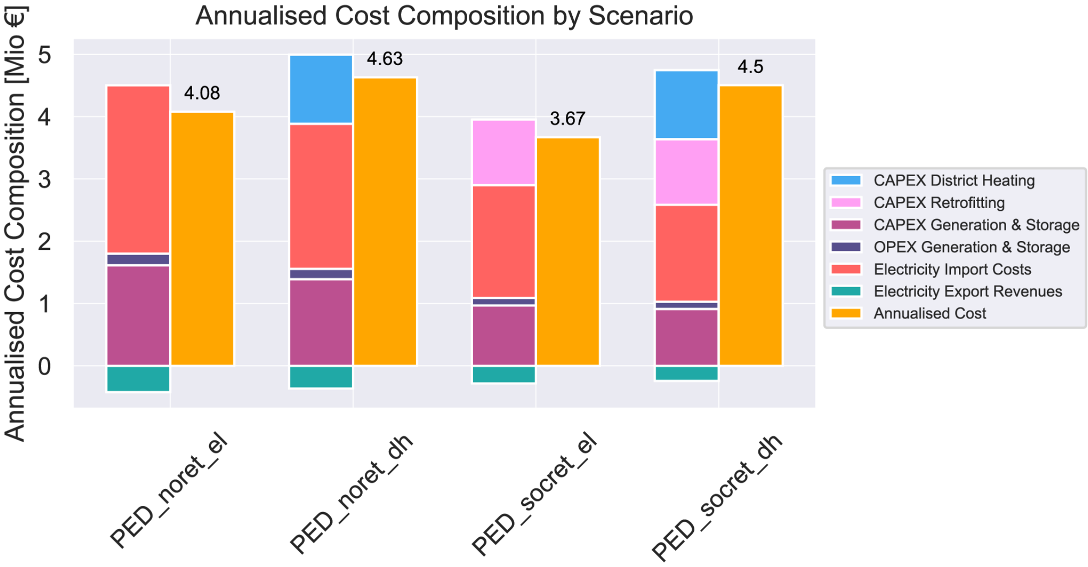


Figure 9: Comparison of the annualised cost of the PED scenarios without EV charging consumption

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 additional electricity demand from EV charging has a relatively small effect on the annualised cost. The cost increases slightly due 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 to transition existing districts into 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 of renewable energy technologies, a lack of building retrofitting could significantly impact meeting sufficient energy demand in PEDs. 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 as arbitrage is not incentivised.

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 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

Details of the ABM scenarios

Two additional scenarios have been considered in modelling the uptake of neighbourhood retrofitting, namely, worst-case and best-case scenarios. Table 13 presents the numerical values and a description of the parameters chosen for the model. The parameters of the medium scenario presented in Section 4.3 lie between these two scenario parameters.

Table 13: Parameters of the Agent-based Model

	(1) Best-case scenario	**(2) Worst-case scenario**	**(3) Medium scenario**	**Explanation of the variables and the impact**
Uncertainty due to the presence of intermediary	***Reduced***	***Increased***		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
opinion_threshold	-0,7	0,3	0	
Connectedness and interaction in the neighbourhood	***Well-connected and sociable neighbours***	***Less well-connected and less sociable neighbours***		mu is the parameter that decides how strongly an agent is influenced by somebody else's opinion upon random interaction. Same for all agents
mu	0,5	0,1	0,25	
gamma	0,3	0,1	0,25	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	2	
Specific cost reduction due to group purchase	***Higher***	***Lower***		group factor is the parameter that decides how strongly the costs reduce. Higher group factor means that costs reduce more drastically depending on the number of buildings agreeing to renovate
group factor	0,05	0,01	0,02	
Subsidies	***Higher subsidies***	***Lower subsidies***		Subsidy for agents (EUR/agent) increases the affordability of the renovation options. Same amount for everybody
subsidy	5000	0	0	

The results of the two additional scenarios are shown in Figures 10 and 11. The results indicate that with the positive assumption it is possible to achieve 74% heat demand reduction (as compared to initial heat demand of the neighbourhood) in the neighbourhood and almost 99,7% of total gross floor area is insulated in this case. According to the worst-case scenario already about 20% of space heat demand reduction would be achieved with only 3,4% of total gross floor area of housing implementing energy-efficient measures.

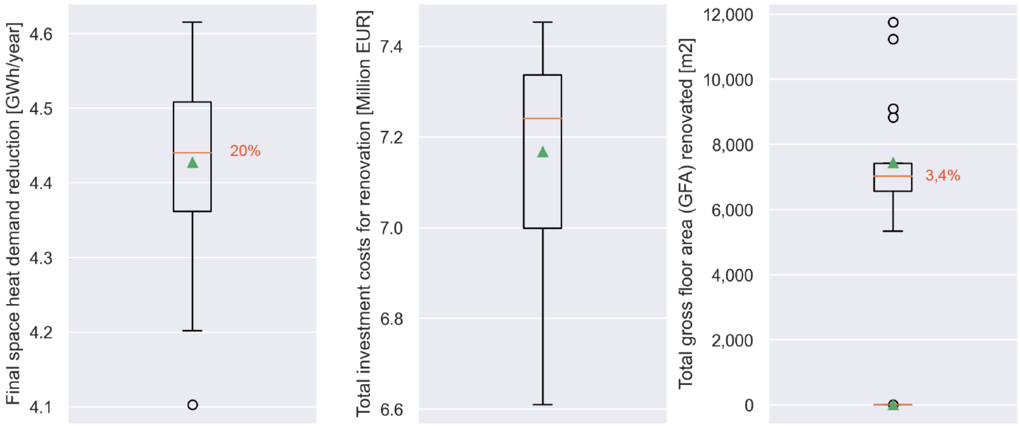


Figure 10: Boxplots of: (1) Reduction in space heat demand [GWh/year], (2) Total cost of renovation [Million EUR], (3) Total GFA of buildings renovated [m2]

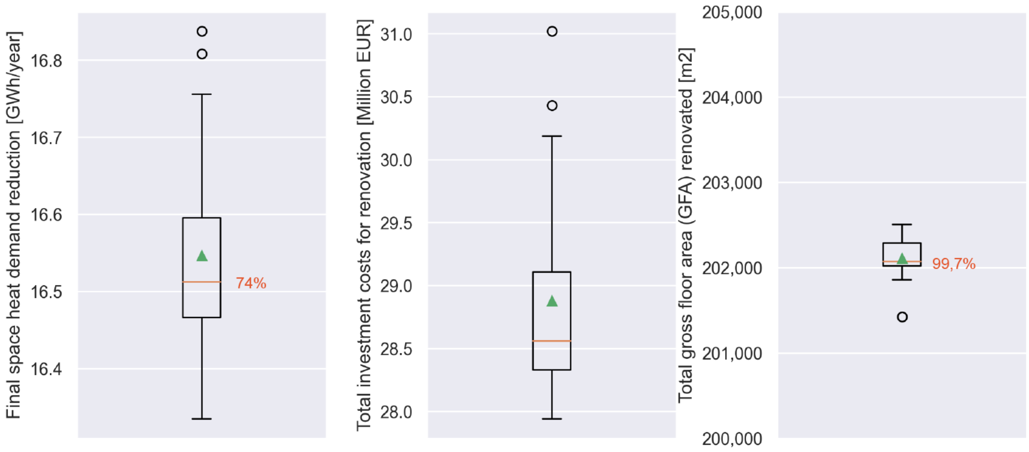


Figure 11: Boxplots of: (1) Reduction in space heat demand [GWh/year], (2) Total cost of renovation [Million EUR], (3) Total GFA of buildings renovated [m2]

Public EV charging infrastructure

Figure 12 presents a map of districts of Frankfurt city. Districts are named by their postcodes and compared in Section 4.4

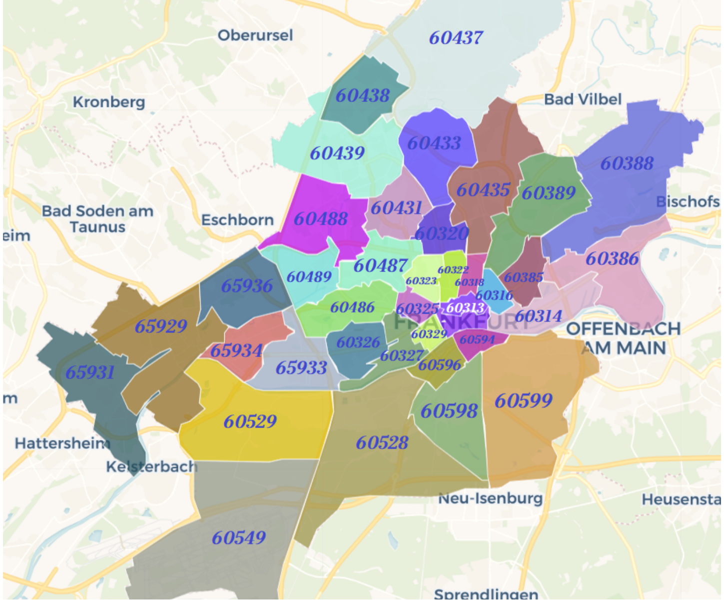


Figure 12: Frankfurt's districts

Figure 13 presents a map of distribution of EV charging points between districts across the city.

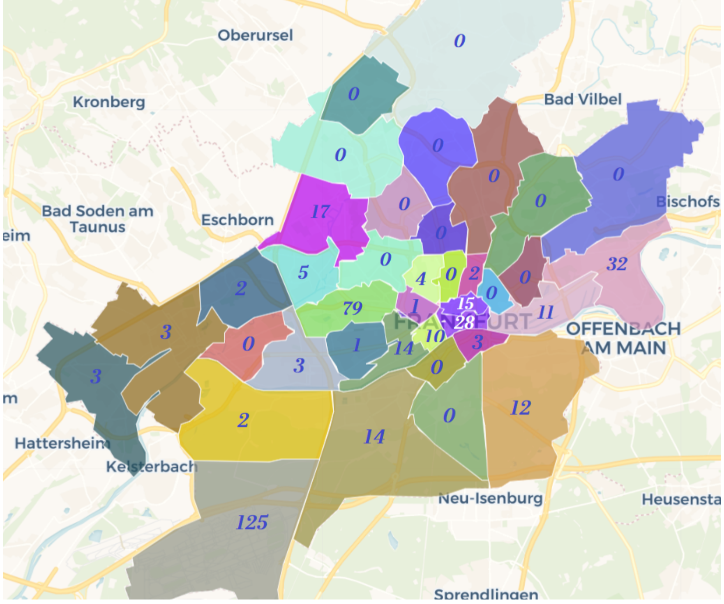


Figure 13: Numbers of public EV charging points per district.

Figure 14 presents weekly demand profile used in scenarios. The profile is averaged over full year for 5 slow and 8 fast public charging points. In weekday, 3 charging sessions per charger with average charging duration of 3 hours for slow public charging and 1 hour for fast charging are estimated. In weekends, 2 charging sessions with average charging duration of 3 hours for slow public charging and 1 hour for fast charging are estimated.

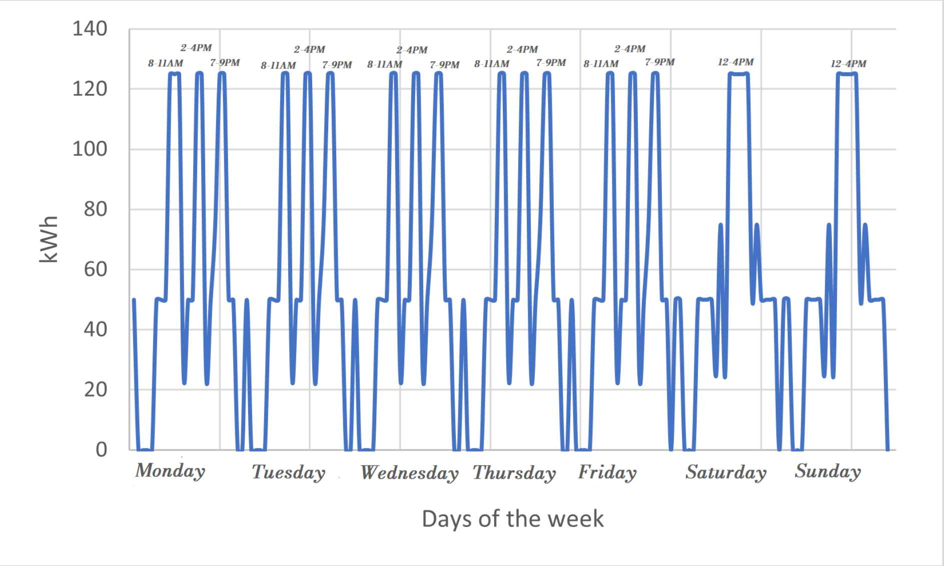


Figure 14: Weekly demand profile of public EV charging points, averaged over full year

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.

The appendix subsection Comparison algorithm shows the code with relevant comment to understand the flow and the functions utilised.

Comparison algorithm

```
"""
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")
```

References

Zwickl-Bernhard, Sebastian and Hans Auer (Jan. 2021). “Open-source modeling of a low-carbon urban neighborhood with high shares of local renewable generation”. In: *Applied Energy* 282, p. 116166. ISSN: 03062619. DOI: 10.1016/j.apenergy.2020.116166.

Fulmer, Jeffrey E (2009). “What is the World Infrastructure?” In: *PEI Infrastructure investor* 1.4, pp. 30–32. URL: https://30kwe1si3or29z2y020bgbet-wpengine.netdna-ssl.com/wp-content/uploads/2018/03/what-in-the-world-is-infrastructure.pdf.

Brozovsky, Johannes, Arild Gustavsen, and Niki Gaitani (Sept. 2021). “Zero emission neighbourhoods and positive energy districts – A state-of-the-art review”. In: *Sustainable Cities and Society* 72, p. 103013. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2021.103013.

JPI Urban Europe (2020). *White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods*. Tech. rep. URL: https://jpi-urbaneurope.eu/ped/.

Bruck, Axel, Luca Casamassima, et al. (2022). “Creating Comparability among European Neighbourhoods to Enable the Transition of District Energy Infrastructures towards Positive Energy Districts”. In: *Energies* 15.13, p. 4720.

Chang, Miguel et al. (May 2021). “Trends in tools and approaches for modelling the energy transition”. In: *Applied Energy* 290, p. 116731. ISSN: 03062619. DOI: 10.1016/j.apenergy.2021.116731.

Goldthau, Andreas (Mar. 2014). “Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism”. In: *Energy Research & Social Science* 1, pp. 134–140. ISSN: 2214-6296. DOI: 10.1016/J.ERSS.2014.02.009.

Cheng, Yaohua et al. (2020). “Planning multiple energy systems for low-carbon districts with high penetration of renewable energy: An empirical study in China”. In: *Applied Energy* 261, p. 114390. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2019.114390. URL: https://www.sciencedirect.com/science/article/pii/S030626191932077X.

Comodi, Gabriele et al. (2019). “Achieving low carbon local energy communities in hot climates by exploiting networks synergies in multi energy systems”. In: *Applied Energy* 256, p. 113901. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2019.113901. URL: https://www.sciencedirect.com/science/article/pii/S0306261919315880.

Capuder, Tomislav and Pierluigi Mancarella (2016). “Assessing the benefits of coordinated operation of aggregated distributed Multi-energy Generation”. In: *2016 Power Systems Computation Conference (PSCC)*, pp. 1–7. DOI: 10.1109/PSCC.2016.7540829.

Bartolini, Andrea et al. (2018). “Optimal Planning of Low Carbon Microgrids Using Primary Energy Savings as a Constraining Factor: The Case of an Industrial Retrofit”. In: *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, pp. 1–6. DOI: 10.1109/EEEIC.2018.8494533.

Del Pero, C et al. (2019). “Modelling of an Integrated multi-energy system for a nearly Zero Energy Smart District”. In: *2019 International Conference on Clean Electrical Power (ICCEP)*. IEEE, pp. 246–252.

Gabaldón Moreno, Andrea et al. (2021). “How to Achieve Positive Energy Districts for Sustainable Cities: A Proposed Calculation Methodology”. In: *Sustainability* 13.2. ISSN: 2071-1050. DOI: 10.3390/su13020710. URL: https://www.mdpi.com/2071-1050/13/2/710.

Garau, M et al. (2017). “Tecno-economic and environmental assessment of a full electric smart city eco-district”. In: *2017 AEIT International Annual Conference*. IEEE, pp. 1–6.

Ge, Xiubei et al. (2019). “Simulation-supported quantification of flexibility: assessing the potential for blocks of buildings to participate in demand response markets”. In: *2019 16th International Conference on the European Energy Market (EEM)*. IEEE, pp. 1–6.

Hachem-Vermette, Caroline and Kuljeet Singh (2020). “Developing an optimization methodology for urban energy resources mix”. In: *Applied Energy* 269, p. 115066. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2020.115066. URL: https://www.sciencedirect.com/science/article/pii/S030626192030578X.

Heendeniya, Charitha Buddhika, Andreas Sumper, and Ursula Eicker (2020). “The multi-energy system co-planning of nearly zero-energy districts – Status-quo and future research potential”. In: *Applied Energy* 267, p. 114953.

ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2020.114953. URL: https://www.sciencedirect.com/science/article/pii/S0306261920304657.

Kim, Min-Hwi et al. (2019). "Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community". In: *Energy* 187, p. 115916. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2019.115916. URL: https://www.sciencedirect.com/science/article/pii/S0360544219315944.

Koutra, Sesil, Vincent Becue, and Christos S. Ioakimidis (2016). "From the 'smart ground' to the 'smart city': An analysis of ten European case-studies". In: *2016 5th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS)*, pp. 1–6.

Morales González, R. et al. (2012). "Distributed energy resources for a zero-energy neighborhood". In: *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, pp. 1–8. DOI: 10.1109/ISGTEurope.2012.6465820.

Pinel, Dimitri, Sigurd Bjarghov, and Magnus Korpås (2019). "Impact of grid tariffs design on the zero emission neighborhoods energy system investments". In: *2019 IEEE Milan PowerTech*. IEEE, pp. 1–6.

Pinel, Dimitri, Magnus Korpås, and Karen B. Lindberg (2020). "Cost Optimal Design of Zero Emission Neighborhoods' (ZENs) Energy System". In: *Advances in Energy System Optimization*. Ed. by Valentin Bertsch et al. Cham: Springer International Publishing, pp. 145–163. ISBN: 978-3-030-32157-4.

Pietruschka, Dirk et al. (2015). "Decentralised heat pumps and small electricity storages as active components in a virtual power plant for smart grid services". In: *2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)*, pp. 737–741. DOI: 10.1109/EEEIC.2015.7165256.

Aste, N et al. (2017). "Smart-grid and smart-districts: Case-study and techno-economic analysis". In: *6th International Conference on Clean Electrical Power, ICCEP 2017*. Institute of Electrical and Electronics Engineers Inc., pp. 23–29.

Aste, Niccolò et al. (2020). "A renewable energy scenario for a new low carbon settlement in northern Italy: Biomass district heating coupled with heat pump and solar photovoltaic system". In: *Energy* 206, p. 118091. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2020.118091. URL: https://www.sciencedirect.com/science/article/pii/S0360544220311981.

Kılkış, Şiir (2014). "Energy system analysis of a pilot net-zero exergy district". In: *Energy Conversion and Management* 87, pp. 1077–1092. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2014.05.014. URL: https://www.sciencedirect.com/science/article/pii/S0196890414004257.

Rezaei, Abolfazl et al. (2021). "A New Modeling Approach for Low-Carbon District Energy System Planning". In: *Energies* 14.5. ISSN: 1996-1073. DOI: 10.3390/en14051383. URL: https://www.mdpi.com/1996-1073/14/5/1383.

Renaldi, R., A. Kiprakis, and D. Friedrich (2017). "An optimisation framework for thermal energy storage integration in a residential heat pump heating system". In: *Applied Energy* 186. Sustainable Thermal Energy Management (SusTEM2015), pp. 520–529. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2016.02.067. URL: https://www.sciencedirect.com/science/article/pii/S0306261916302045.

Roccamena, Letizia, Mohamed El Mankibi, and Nikolaos Stathopoulos (2019). "Development and validation of the numerical model of an innovative PCM based thermal storage system". In: *Journal of Energy Storage* 24, p. 100740. ISSN: 2352-152X. DOI: https://doi.org/10.1016/j.est.2019.04.014. URL: https://www.sciencedirect.com/science/article/pii/S2352152X18307849.

Sameti, Mohammad and Fariborz Haghighat (2018). "Integration of distributed energy storage into net-zero energy district systems: Optimum design and operation". In: *Energy* 153, pp. 575–591. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2018.04.064. URL: https://www.sciencedirect.com/science/article/pii/S0360544218306716.

Shafiullah, Dewan Siam, Thai H Vo, and PH Nguyen (2018). "A heuristic search approach for sizing battery storage of a neighbourhood including nearly Zero Energy Buildings (nZEB)". In: *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*. IEEE, pp. 1–6.

Shaw-Williams, Damian et al. (2020). "Towards net-zero energy neighbourhoods utilising high rates of residential photovoltaics with battery storage: a techno-economic analysis". In: *International Journal of Sustainable Energy*

39.2, pp. 190–206. DOI: `10.1080/14786451.2019.1668394`. eprint: `https://doi.org/10.1080/14786451.2019.1668394`. URL: `https://doi.org/10.1080/14786451.2019.1668394`.

Rose, Jørgen et al. (2021). “Building renovation at district level – Lessons learned from international case studies”. In: *Sustainable Cities and Society* 72, p. 103037. ISSN: 2210-6707. DOI: `https://doi.org/10.1016/j.scs.2021.103037`. URL: `https://www.sciencedirect.com/science/article/pii/S2210670721003218`.

Paiho, Satu et al. (2019). “A new procedure for assessing the energy-efficient refurbishment of buildings on district scale”. In: *Sustainable Cities and Society* 46, p. 101454. ISSN: 2210-6707. DOI: `https://doi.org/10.1016/j.scs.2019.101454`. URL: `https://www.sciencedirect.com/science/article/pii/S2210670718324399`.

Fina, Bernadette, Hans Auer, and Werner Friedl (May 2019). “Profitability of active retrofitting of multi-apartment buildings: Building-attached/integrated photovoltaics with special consideration of different heating systems”. In: *Energy and Buildings* 190, pp. 86–102. ISSN: 03787788. DOI: `10.1016/j.enbuild.2019.02.034`.

Chicherin, Stanislav et al. (2020). “Method for assessing heat loss in a district heating network with a focus on the state of insulation and actual demand for useful energy”. In: *Energies* 13.17. ISSN: 19961073. DOI: `10.3390/en13174505`.

Kottek, Markus et al. (July 2006). “World Map of the Köppen-Geiger climate classification updated”. In: *Meteorologische Zeitschrift* 15.3, pp. 259–263. ISSN: 09412948. DOI: `10.1127/0941-2948/2006/0130`.

Akhatova, Ardak, Axel Bruck, and Luca Casamassima (2020). *D4.2 Techno-economic Aspects and Pathways towards Positive Energy Districts Status quo and framework conditions as a basis for developing techno-economic pathways in selected case studies*. Tech. rep.

Fischer, David et al. (2016). “A stochastic bottom-up model for space heating and domestic hot water load profiles for German households”. In: *Energy and Buildings* 124, pp. 120–128. DOI: `10.1016/j.enbuild.2016.04.069`.

Hersbach, H. et al. (2018). *ERA5 hourly data on single levels from 1979 to present*. DOI: `10.24381/cds.adbb2d47`. (Visited on 07/16/2021).

Bruck, Axel, Santiago Díaz Ruano, and Hans Auer (Aug. 2021). “A Critical Perspective on Positive Energy Districts in Climatically Favoured Regions: An Open-Source Modelling Approach Disclosing Implications and Possibilities”. In: *Energies* 14.16. DOI: `10.3390/EN14164864`.

Eurostat (2021). *Electricity price statistics - Statistics Explained*. URL: `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics` (visited on 05/20/2021).

Bruck, Axel, Santiago Díaz Ruano, and Hans Auer (Sept. 2022). “One piece of the puzzle towards 100 Positive Energy Districts (PEDs) across Europe by 2025: An open-source approach to unveil favourable locations of PV-based PEDs from a techno-economic perspective”. In: *Energy* 254, p. 124152. ISSN: 03605442. DOI: `10.1016/j.energy.2022.124152`.

Bruck, Axel, Santiago Diaz Ruano, and Hans Auer (Sept. 2022). “Values and implications of building envelope retrofitting for residential Positive Energy Districts”. In: *Energy and Buildings*, p. 112493. ISSN: 0378-7788. DOI: `10.1016/J.ENBUILD.2022.112493`.

Sveinbjörnsson, Dadi et al. (2019). *D2.3 Large Storage Systems for DHC Networks*. URL: `www.flexynets.eu`.

oysal, Emilie Rosenlund et al. (2016). “Electric Boilers in District Heating Systems: A Comparative Study of the Scandinavian market conditions”. In: *Swedish Association for Energy Economics Conference 2016*. URL: `http://www.ltu.se/research/subjects/Nationalekonomi/Konferenser/SAEE2016`.

Zühlsdorf, B et al. (2019). “Industrial Heat Pumps,Second Phase”. In:

Koch et al. (2021). “Anpassung der Kostenfunktionen energierelevanter Bau- und Anlagenteile bei der energetischen Modernisierung von Altbauten auf das Preisniveau 2020. Werkstattbericht.” In: URL: `www.iwu.de`.

Vesterlund, Mattias et al. (n.d.). “EVALUATION OF LOSSES IN DISTRICT HEATING SYSTEM, A CASE STUDY”. In: ().

Eurostat (2022). *Electricity prices for household consumers - bi-annual data (from 2007 onwards) (online data code: NRG_PC_204)*. URL: `https://tinyurl.com/4zzr7c2j` (visited on 09/27/2022).

Deutschland, Statistisches Bundesamt (2022). *Erdgaspreise fuer Haushalte: Deutschland, Halbjahre, Jahresverbrauchsklassen, Preisarten*. URL: `https://tinyurl.com/m7bdptya` (visited on 09/27/2022).

Main, Stadtplanungsamt Frankfurt am (2019). *Stadtumbau Hessen, Griesheim-Mitte Integriertes Staedtebauliches Entwicklungskonzept (ISEK)*. Tech. rep. URL: `https://tinyurl.com/47thpe8d`.

GoogleMap (n.d.). Accessed: 2022-07-22. URL: `http://web.archive.org/web/20080207010024/http://www.808multimedia.com/winnt/kernel.htmhttps://www.google.com/maps/search/ev+charging+stations+60314/@50.1082286,8.6569369,13z`.

Soylu, Tamer et al. (2016). "Building up demand-oriented charging infrastructure for electric vehicles in Germany". In: *Transportation Research Procedia* 19, pp. 187–198.

Hall, Dale and Nic Lutsey (2020). "Charging infrastructure in cities: Metrics for evaluating future needs". In: *Europe* 6.7,000,000, pp. 8–000.

Baumgarte, Felix, Matthias Kaiser, and Robert Keller (2021). "Policy support measures for widespread expansion of fast charging infrastructure for electric vehicles". In: *Energy Policy* 156, p. 112372.

Balgaranov (2022). Accessed: 2022-07-22. URL: `https://tinyurl.com/4j2k56cm`.

Gilleran, Madeline et al. (2021). "Impact of electric vehicle charging on the power demand of retail buildings". In: *Advances in Applied Energy* 4, p. 100062.

Andrenacci, Natascia, Federico Karagulian, and Antonino Genovese (2022). "Modelling charge profiles of electric vehicles based on charges data". In: *Open Research Europe* 1.156, p. 156.

Mortimer, Benedict J et al. (2021). "Public Charging Infrastructure in Germany—A Utilization and Profitability Analysis". In: *Journal of Modern Power Systems and Clean Energy* 99, pp. 1–10.