Work Package 4 | Task 4.3

D4.4 - Report on developed methodologies and models for techno-economic modelling of PEDs and the transition towards their realisation

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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Executive Summary

In the light of urgent need for decarbonisation of the building sector, techno-economic modelling of energy systems is an essential part of the planning process of urban development. Positive Energy Districts (PEDs) should contribute to this transformation towards less carbon-intensive and more energy independent urban areas. Therefore, this report presents the techno-economic models that have been developed throughout the Smart-BEEjS project to determine the energy infrastructure required to transform current districts into PEDs.

This report reviews the existing models that focus on the district and neighborhood energy modelling (Section 2). The literature emphasises that existing models are not sufficient for PED planning, as PED analysis requires a large diversity of data inputs and have very specific modelling requirements. Moreover, it is important to further advance an integrated systems approach that brings together techno-economic and social aspects with sufficient detail.

Four modelling approaches address four different sectors of the PED's energy infrastructure that needs to be included in the planning of the transition from exiting districts to PEDs. The electricity based system, including local renewable energy generation and electricity-based heating and cooling is covered by a mixed integer linear programming approach to guarantee an optimal technology portfolio while ensuring a positive energy balance (Section 3.1). The heating and cooling system is focusing on district solutions such as 4^{th} generation district heating/cooling with a mathematical approach (Section 3.2). The energy efficiency uptake of the building stock is addressed by agent based modeling (Section 3.3). Finally, the electric vehicle related charging infrastructure is modelled using statistics on real data (Section 3.4). Furthermore, as sector coupling is highly important these days, the interconnections of the presented models are drawn (Section 3.5). The models include important social factors such as affordability, inclusiveness and energy justice that is often not the focus of mainstream techno-economic models. As affordability, inclusiveness and energy justice are cornerstones of the PED concept, the models aim to address those values.

The combined model can holistically evaluate what energy infrastructure is needed to transition from current districts to high-performance PEDs.

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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) has been elaborated by the European Commission (EC) and introduced in the Strategic Energy Technology Plan (SET-Plan). This Plan is one of the key tools to deliver the EU strategy for the energy transition, where an ambitious target towards developing 100 PEDs in Europe by 2025 at least in the planning phase has been established (European Commission 2018). A PED is required to export more energy annually than it imports from outside the district boundaries (European Commission 2018; Casamassima et al. 2022). Furthermore, a PED shall provide a high standard of living, while being inclusive and just (JPI Urban Europe 2020).

The transition towards PED can only be achieved by transforming the current energy infrastructure as urban areas historically have a large imbalance of energy demand and supply. To become a PED, the local supply needs to meet the local demand of the district. Thus, energy infrastructure in PEDs has to set the focus on reducing demand and on local renewable energy supply. District energy infrastructure is defined in this report as the physical parts of building and energy systems (i.e. generation technology, heating network, electricity grid) that supply energy services (e.g. electric appliances, space heating, domestic hot water (DHW), electric vehicles) essential to enable, sustain and enhance societal living conditions (Fulmer 2009; Brozovsky et al. 2021).

The transition towards highly ambitious energy concepts such as the PED require planning activities to determine the infrastructure needed in a specific location. The main steps of planning the energy infrastructure to get from an existing district to a PED are illustrated in Figure 1. In planning a PED, first, the status quo of the district, including the renovation status of buildings, the current energy demand, the rooftop area available for PV generation and the existing heating infrastructure needs to be analysed (Akhatova, Bruck, et al. 2020). Secondly, passive interventions that typically reduce the energy demand should be evaluated. This includes retrofitting of the building envelope, shading, low power appliances, to mention a few (Sections 3.2 and 3.3). The planning of active infrastructure is based on the building energy demand that is previously lowered by passive interventions (Fina et al. 2019). Therefore, a technology portfolio is planned such that it fulfills the the energy demand of the district, is economical and meets other requirements (e.g. energy positive) (Section 3.1). A typical technology portfolio of a PED could include such mature technologies as photovoltaic systems (PV), heat pumps, energy storage system and electric vehicle (EV) charging facilities. Additionally, facilitation of the switch towards more sustainable transport modes includes making electric vehicle charging points accessible to district residents (Section 3.4).

The challenges of the energy transition is not only of the technical nature but also of socio-economic one (SET-Plan Working Group 2018). Affordability, inclusiveness and energy justice are essential aspects of the energy transition (SET-Plan Working Group 2018). Energy justice analyses where injustices emerge, which sections of society are ignored and what processes could remediate such injustices (Jenkins et al. 2016). Energy is a basic need that humanity prises, and its distribution, in terms of benefits and burdens, should be highly prioritised to guarantee a fair society (Sovacool 2014). In these terms, every person should be able to decide whether to access energy services or not. The inability to do so is typically referred to as fuel poverty (or energy poverty). The causes are usually economical, rooted in low incomes, high energy prices, high rents and poor housing quality.

To support the planning transition steps of PEDs (Figure 1), this report elaborates on modelling activities focused on either passive or active interventions (or account for both) (Section 3). Together these methods make up a holistic planning approach (Section 3.5). The common output facilitates the pro-

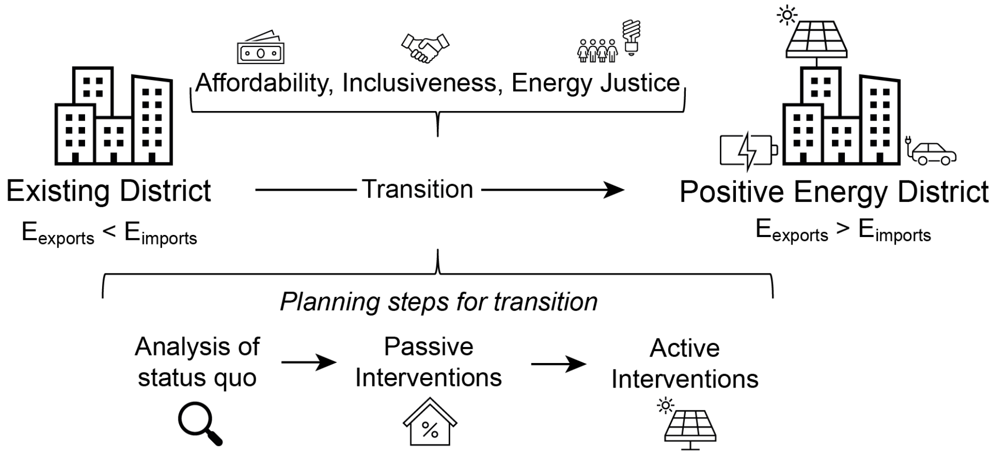

Figure 1: Transition Steps towards PED realisation

cess of defining the infrastructure necessary for an existing district to become a PED. It is supported by a literature review of existing district-wise energy models (Section 2). The work performed as part of the SMART-BEEjS projects aims to fill the identified gaps in the literature, by developing new tailored models and utilising already available tools and methods.

Moreover, the report discusses the necessary steps to be taken during the planning phase of a PED, highlighting crucial aspects that need to be covered during the planning activity. One core aspect of PEDs is ensuring just energy transition, which shifts the focus from a mere technical perspective. The energy justice concept has applied to a wide range of energy issues covering energy production, supply and demand. In this work, energy justice refers to a concept defined "as a global energy system that fairly distributes both the benefits and burdens of energy services, and one that contributes to more representative and inclusive energy decision-making" (Sovacool 2014). Section 3 discuss in detail how the methods and models described within this report assure that these aspects are included in the techno-economic analyses.

The flow chart (Figure 1) described in this report is applied to the Work Package 4 deliverables. A report (D4.2) on the status-quo of selected city has already been produced. It analyses the current status of 4 partner cities (Vienna, Frankfurt, Torres Vedras, Nottingham) to lay the basis for further work. Deliverable 4.3 describes the results from the models described in this report, together with the necessary passive and active energy measures to take in order to transform an existing district into a PED.

2 State of the art in modelling district energy infrastructure

Quantitative energy models help policymakers and building designers to evaluate possible effects of infrastructure changes, including energy retrofitting measures. Hence, they provide an evidence basis and reduce the risks connected to new investments (Bukovszki et al. 2020). Numerous energy system modelling tools which represent energy systems according to different technical and methodological considerations exist currently (Chang et al. 2021). Among this vast landscape we consider three fields of modelling approaches most relevant for modelling of PED infrastructure. That is, the methods used for evaluating demand reduction measures in buildings and assessing the local renewable energy supply infrastructure.

Thermal energy demand in buildings (which constitutes the significant share in many European countries) are reduced by insulating the building envelope and weather-proofing the windows. Bottom-up building energy models are commonly used for evaluating passive building retrofitting measures at the scale of neighbourhoods (Reinhart and Cerezo Davila 2016; Yazdanie and Orehounig 2021). As these types of models offer a detailed view on the technical aspects of the system, another approach is needed for considering other aspects of retrofitting implementation, such as the interaction of stakeholders and investment behaviour of building owners. These are addressed by an agent-based technology diffusion models. In assessing the necessary capacity of renewable supply technologies, techno-economic optimisation is a widely used method which allows to obtain the optimal set of solution. They provide a response to the question, how a certain system should be designed (in order to achieve a certain target and under certain constraints).

Bottom-up building energy models account for the energy consumption of individual buildings or groups of buildings, which makes it a common approach for urban or district building energy models (Reinhart and Cerezo Davila 2016). These models can use statistical or engineering techniques to estimate energy consumption (Swan and Ugursal 2009). At the scale of analysis ranging from a dozen to thousands of buildings, bottom-up engineering models (also called "building physics models") are seen as a key planning tool for utilities, municipalities, urban planners and architects dealing with clusters of buildings (campus, block,neighborhoods, etc) (Reinhart and Cerezo Davila 2016). Conversely, statistical methods (also called data-driven models) rely on historical information and it is hard to analyse savings from energy retrofits with those. Such data-driven models are usually employed to identify operational problems or predict operational changes (Chen et al. 2017). In contrast to optimisation models, bottom-up models respond to "what-if" questions and are used together with exploratory scenarios.

Mathematical optimization is widely considered as an effective methodology to generate insights that inform policy (Scheller and Bruckner 2019). It is also attractive for decision makers as it results in specific recommendations and ensures economically optimal solutions under existing conditions (Scheller and Bruckner 2019). Commonly used optimization techniques are linear programming (LP) and mixed integer linear programming (MILP). Mathematical models of energy systems commonly provide the cost optimal energy technology portfolio and energy dispatch per time step, complying with the described boundary conditions, called constraints. This offers great flexibility to the modelling approach as additional boundary conditions, such as a positive energy balance with the grid can be integrated as a constraint. LP/MILP models are used widely in the literature. Mathematical modelling can be framed to one specific research question or applied for reusable models (Cosic et al. 2021; Pfenninger and Pickering 2018; Dorfner 2016).

Building energy models and techno-economic optimisation models often assume rational decision-making an concentrate on the technical and economic aspects of active and passive retrofitting solutions. However, retrofitting is socio-techno-economic process that involves human behaviour which often involves cognitive biases and are far from rational. Identification of an optimal portfolio or optimal DH strategy does not give an indication of whether district residents will adopt those measures. Agent-based modelling (Du et al. 2022; Rai and Robinson 2015; Moglia, Podkalicka, et al. 2018; Akhatova, Kranzl, et al. 2022) is one of the bottom-up modelling methods used for simulation of technology or innovation diffusion (Du et al. 2022; Rai and Robinson 2015; Moglia, Podkalicka, et al. 2018; Akhatova, Kranzl, et al. 2022; Kiesling et al. 2012; Moglia, Cook, et al. 2017). It can address the heterogeneous nature of households and is a suitable method for evaluating policies, such as subsidies, product bans (Moglia, Cook, et al. 2017; Jensen et al. 2016). This modelling approach is flexible enough to incorporate technical, social, economic and policy factors of energy-efficient retrofitting (Du et al. 2022; Bonabeau 2002). Akhatova, Kranzl, et al. 2022 gives an overview of how it has been done in the context of urban districts.

In transportation planning for policy-making, accessibility indicator is a key measure in characterising or evaluating levels of the access to a facility and in identifying transport related inequities and social exclusion (Ribeiro et al. 2021). In analysing accessibility of public EV charging infrastructure, many literature sources are focused on country- or city-level data, investigating charging infrastructure in a single country/city or comparing them across countries/cities. In this study, accessibility of public EV charging infrastructure is proposed to be analysed at a district level that is according to Elaadnl and Refa 2020 could be useful information in strategic roll-out policies for local governments or municipalities and in quantification of the potential grid impacts of EVs for distribution system operators (DSOs).He 2020 reports that a range of studies, which explored accessibility of charging infrastructure, failed to define the contextual measurement of accessibility. The proposed method for assessing accessibility of EV charging infrastructure in PEDs attempts to fill this gap by comparing the number of public charging points and their charging capacity across districts and identifying potential future needs of public charging infrastructure at a district scale.

Modelling local energy systems in the built environment is different from those for the national energy planning, because it is needed for policy implementation (and not for policy design) (Bouw et al. 2021). Thus, it requires a more detailed characterisation of the local context, such as building characteristics, resource potential, and available infrastructure (Bouw et al. 2021). Previous review articles provide a thorough overview of local scale models, focusing on such aspects as: local context and social factors within techno-economic models (Bouw et al. 2021), optimization at municipal scale (Scheller and Bruckner 2019), integrated community energy system (Koirala et al. 2016; Mendes et al. 2011), community planning (Huang et al. 2015), district-scale models (Allegrini et al. 2015), and urban energy models (Reinhart and Cerezo Davila 2016; Keirstead et al. 2012). Among the prominent holistic models, Fonseca et al. 2016 offers an integrated framework that holistically evaluates options of building and infrastructure retrofit and determines optimal energy generation schemes. Additionally, it allows the analysis of energy, carbon and financial benefits of multiple urban scenarios and infrastructure options (Fonseca et al. 2016).

The main deficiency of local-scale models is a lack of integrated systems approach that brings together techno-economic and social aspects with sufficient detail (Bouw et al. 2021). As (Bouw et al. 2021) emphasise a combination of interconnected methods is needed for modelling a diverse socio-technical context. Furthermore, (Belda et al. 2022) analyse the challenges of using existing models for PED planning and studies. They conclude that PED analysis require a large diversity of data inputs and have very specific modelling requirements and thus, existing models are not sufficient for PED planning. Hence, this work connects four different PED analysis approaches to address the techno-economic dimension (i.e. demand and supply infrastructure), as well as the socio-economic dimension (accessibility, affordability, energy justice). In this way, we ensure that the complexity of PED planning is addressed holistically.

3 Models and methods developed for PED transition planning

In this section we elaborate upon the models that are being developed within the Smart-BEEjS project and their specific focus compared to existing approaches. Furthermore, this work discusses how the models reflect on affordability, inclusiveness and energy justice and whether it the aim is rather related to PED planning or its transition towards realisation. Finally, we present an approach to categorise districts to select a common case study to apply the models.

As PEDs focus on a people-centred approach, the importance of assessing indicators such as affordability, social inclusion and energy justice is recognised and considered in developed models and methods. Within this context, it is essential to provide energy at affordable prices, as well as building renovations and proper mobility infrastructure. The models developed challenge these issues by providing a techno-economical analysis of photovoltaic panels, battery storage, BEV chargers diffusion, building energy renovations and their uptake in the district. Ultimately, these topics combined do not only cover the affordability of the energy provision but also their geographical distribution. Hence, the models described in this chapter can help tackling energy poverty and distributional justice through a techno-economical analysis of the energy system and its potential transformation.

3.1 PEDso - Positive Energy District system optimiser

Electrification of heating and cooling is considered to be one of the pillars of decarbonisation of the residential sector, especially where district heating is not available nor feasible (Bruck, Díaz Ruano, et al. 2022). Thus, the electricity-based, multi-energy supply of the energy demand is of crucial importance in PED projects. In order to optimise the energy supply in those districts, PEDso, the Positive Energy District system optimiser has been developed. PEDso is a tailor-made mixed integer linear programming (MILP) model for PED system planning and analysis. It is available under an open-source license at (Bruck 2021). The model is written in Python and based on the open-source Pyomo optimisation extension (Hart, Laird, et al. 2017; Hart, Watson, et al. 2011). Figure 2 shows the conceptual design of the mathematical model, including its input data requirements, the optimisation core and the results of the model. PEDso answers questions regarding the local feasibility of an electrified PED concept, regarding the cost optimal technology portfolio and its operation throughout the project time horizon.

PEDso differs from other mathematical energy system models mainly by the PED specific constraint around the annual energy balance. Equation 1 shows this annual balance constraint.

$$\sum_{ts=0}^{Y}\sum_{c}^{C}(e_{c,ts}^{im} * PEF_{ts}^{im}) < \sum_{ts=0}^{Y}\sum_{c}^{C}(e_{c,ts}^{ex} * PEF_{ts}^{ex}) \tag{1}$$

Y stands for year, ts for timestep, C for the vector of energy carriers, c for a specific energy carrier, e for Energy, im for import, ex for export and PEF stands for renewable primary energy factor.

Equation 1 requires the accumulated energy imports from the out scope to be smaller than the accumulated exports to the outer scope within one year. To compare different forms of energy (electricity, heating, etc.) the primary energy factor is used. This can be chosen to be time-dependent if data is available or static. For the entire mathematical elaboration of the MILP model, as well as its possible application please refer to (Bruck, Díaz Ruano, et al. 2022; Bruck, Santiago Díaz Ruano, et al. 2021; Bruck, Santiago Diaz Ruano, et al. 2022). PEDso covers mainly the analysis of the status quo and the active interventions of the energy infrastructure from the transition steps (Figure 1) but can also be used for

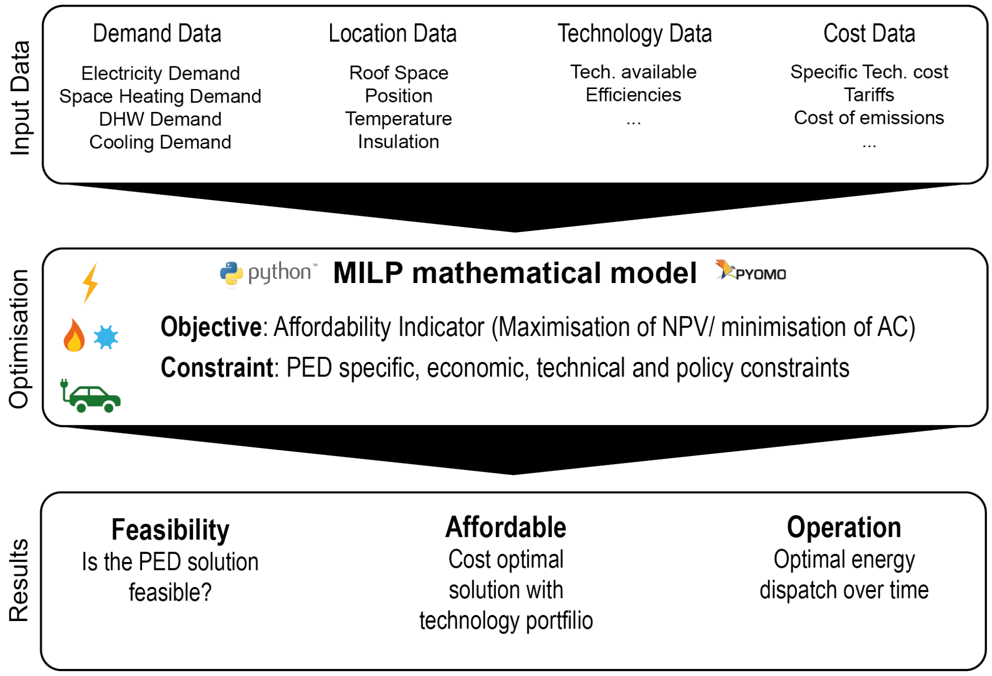

Figure 2: PEDso - conceptual model

testing passive interventions such as building envelope retrofitting in an adapted version. The status quo district analysis goes in the input of the model as shown in Figure 2. The spatial analysis of available rooftop area, and the energy demands are of particular importance. Other location specific data such as the solar insulation can be taken from public sources. The objective of the model is to increase the affordability of the PED solution for the whole community. To do so, PEDso optimises the required capacity of energy infrastructure and the energy flows per time step. The technology portfolio available is shown in 1. Technology that has electricity as an energy input can draw import from the local grid and technology that outputs electricity can export to the grid. The technology can feed electricity among each other (e.g. PV to heat pump). Finally, the three energy demands (electricity, space heating and domestic hot water and space cooling) need to be covered. EV charging infrastructure is only preliminary implemented and still requires testing. Figure 3 shows the interactions of the available technology portfolio without the EV charging infrastructure, which still requires proper integration.

Table 1: Technology portfolio available in PEDso (*preliminary)

Technology	Energy in	Energy out
Solar PV	Solar radiation	Electricity
Battery	Electricity	Electricity
Heat pump (AS and GS)	Electricity	Heat
Electric Boiler	Electricity	Heating and cooling
Thermal Storage	Heat	Heat
EV charging*	Electricity	Electricity

Figure 3 shows the interactions of the available technology portfolio.

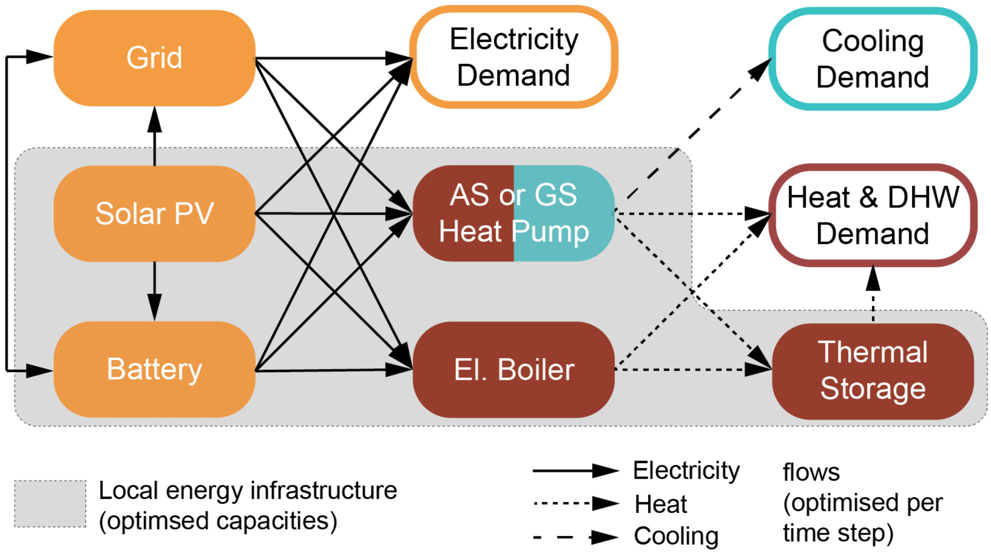

Figure 3: PEDso - Technology interactions (Bruck, Santiago Diaz Ruano, et al. 2022)

The disaggregation of individual costs and obligations is out of the scope of PEDso. However, finding the most affordable community-based solution for a specific case is crucial to then investigate business models for sharing the costs and responsibilities fairly among community members (e.g. see Smart BEEjS deliverable D6.2 - Value generation by PEDs: Best practices case study book).

The model has high significance for decision/policy makers and city planners. Certain scenarios can be compared by varying input parameters such as tariffs or CO_2 costs. Thus, decision makers can find out which parameters are preferable for a PED solution in the local context.

3.2 District Heating Model

The final objective of this modeling activity is to understand possible options and their related costs for district heating grids. The model focuses on high and low temperature heating grids. It accounts for existing excess heat, heat savings in buildings, and compares solutions regarding high and low temperature grids to individual heat supply. In the first stage, the building renovations necessity is assessed first using EnergyPlus. A common radiator (e.g. type 22) works at a nominal temperature of about 70 °C. When the temperature is lower, the radiator works below its rated power, but this does not decrease linearly. A lower supply temperature might decrease the rated power of a radiator to the point that it is not able anymore to guarantee a comfortable temperature. EnergyPlus performs a dynamic building simulation to assess whether the current state of a building can support lower supply temperature without changing the heating system. This helps determine whether a certain energy efficiency renovation level can guarantee an appropriate level of comfort, in this case set as 20 °C during winter season. The objective is to understand what is the level of envelope insulation necessary to allow low temperature heating in a dwelling. Additionally, the total cost of renovation, Net Present Value (NPV) and sensitivity analysis of the system to energy prices are also performed. The study analyses 4 building archetypes in Germany, and supplies key information (renovation costs, insulation levels, specific energy demand [kWh/m2/y], to name a few) to the district heating model. *TABULA WebTool* 2022 provides valuable information on building archetypes. These data include construction typologies, such as window types, walls and roof constructions to mention a few. Tabula and images in the neighbourhood of Griesheim-Mitte, provide data regarding the geometry of the buildings. After the building is identified and constructed in Energy Plus, schedules, room types, heating systems, and distribution are added. Schedules define heat demand through temperature set points but also natural ventilation. For this analysis, the temperature is 20 °C during the heating season. Given the overall aim of this study, the authors do not account for cooling. The set point during the summer season is not set, and the temperature is allowed to oscillate naturally. Tabula maintains natural and unwanted ventilation to 0.5 volumes/hour. To maintain consistency and comparability, the ventilation schedule and value are also 0.5 in Energy Plus. Radiators compose the heating system in the apartments powered by district heating. Figure 4 shows an example of the heating system employed in EnergyPlus.

The side above the middle dashed line represents the supply, while the side below the demand. According to the scenario, district heating provides temperature at different temperatures. In the high-temperature scenario, District Heating (marked with number 1 in the figure) provides heat at 80 °C. Water flows through an adiabatic pipe (2) and reaches the building (4). A variable speed water pump (5) keeps the water circulating. A temperature setpoint (3) maintains the temperature at the given value. The models are calibrated based on the data provided by Tabula. After calibration, the EnergyPlus simulates the building response to high and low-temperature heat. Initially, EnergyPlus simulates the buildings without any renovation scheme to assess their thermal response. Subsequently, different insulation thicknesses (1, 2.5, 5, 10, 15 and 20 cm) and new triple-glazing windows are tested. The supply temperature to the heating system is lowered to 45 °C, and the building's thermal response is tested. Initially, the building is tested with no renovation measures to assess whether it is possible to lower the supply temperature without envelope improvements. The authors then check whether the apartment kept an inside temperature of 20 °C for each renovation package. EnergyPlus also calculates the yearly useful heating demand. Subsequently, renovation costs are calculated with the Net Present Value (NPV), using available literature data to assess the investment's economic viability.

In the second stage, the entire district and its heat supply options are the aim. Here, the model accounts also for existing excess heat in the area. The aim is to understand what are economically viable pathways for heating in districts. Different scenarios are analysed. A scenario in which all buildings can already utilise low temperature heating and hence there will not be a need for booster heat pumps, but costs for renovating the building stock will be taken into account. Secondly a scenario in which buildings are not able to receive low temperature heat, but booster heat pumps bring the temperature to usable levels. In this case there will also be a difference between using heat pumps at the source or at the sink. The model utilises data from existing tools, such as Thermos and Hotmaps. Thermos provides In the first case the grid will still be at high temperature, while in the second case the grid will be at low temperature. A lower temperature in the grid will decrease thermal losses and hence costs, but on the other hand might required a higher mass flow, increasing hydraulic losses. The model estimates the total costs of the different scenarios as:

$$TotalCosts = \sum(C_{savings} + C_{heatdistr} + C_{supplyind} + C_{distrnetwork} + C_{supplycentr}) \quad (2)$$

Where $C_{savings}$ represents the costs of renovating buildings to lower heat demand and supply temperature, $C_{heatdistr}$ is the cost of changing the heat distribution system in buildings, $C_{supplyind}$ is the cost of installing and operating heat pumps at building level to boost the grid tempreature, $C_{distrnetwork}$ is the cost of updating the distribution grid and its related thermal and hydraulic losses, $C_{supplycentr}$ is the

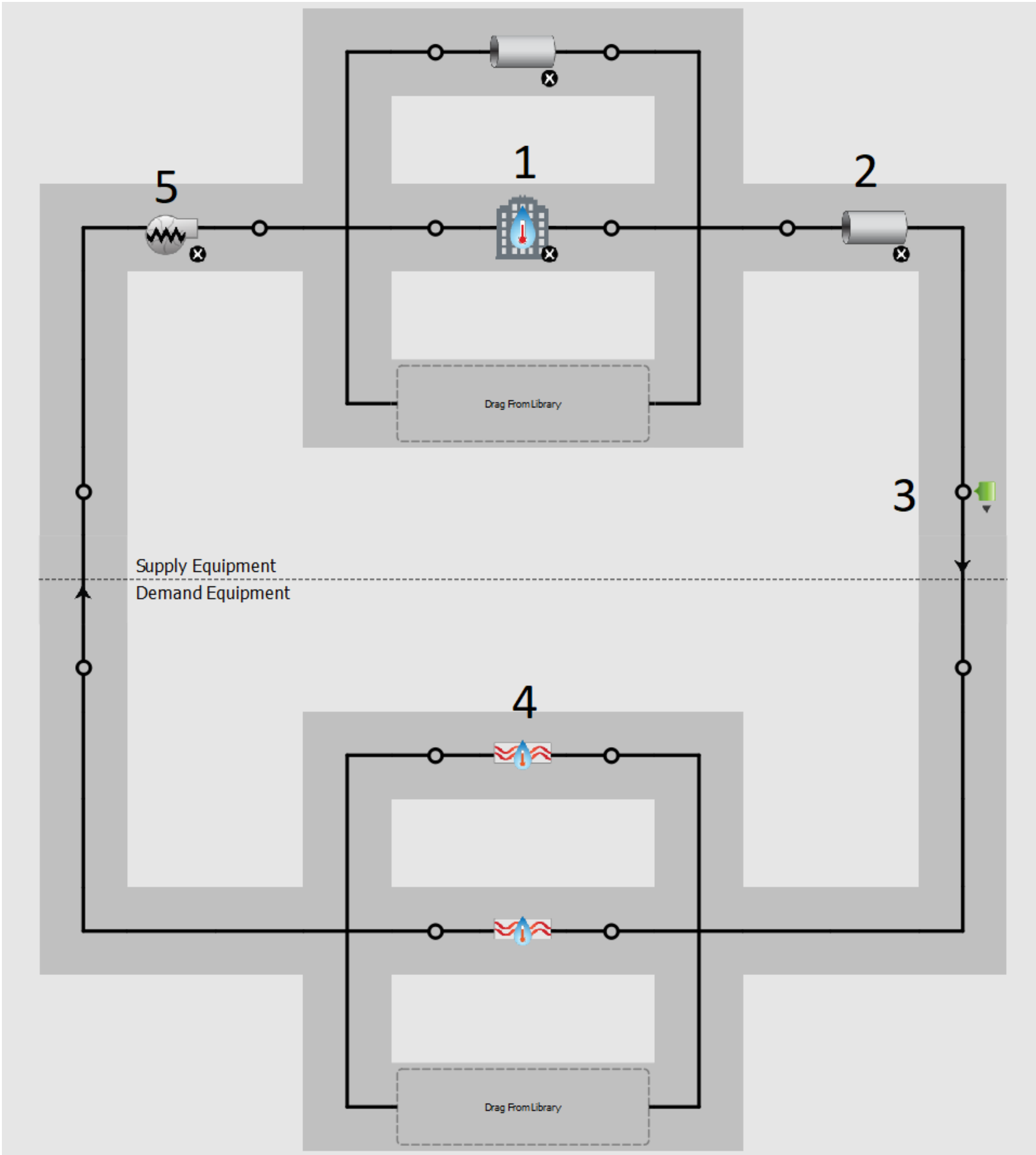

Figure 4: Example of District Heating model in EnergyPlus

cost of installing and operating centralised heat pumps.

3.3 Agent-based model of neighborhood-level retrofitting

Determining the infrastructure required for an existing district to become a PED has been so far predominantly a techno-economic question. Having defined the pathways of optimal mix of supply technologies, including decentralised and individual PV and heat pumps (Section 3.1) and district heating requirements (Section 3.2), it is now of immense importance to see how these technologies would be adopted by district's residents. In the context of neighbourhoods, the actors who make decisions about retrofitting are owners of buildings: social housing companies and private developers or building owners who rent apartments to tenants, owner-occupiers of single homes and apartments in a multi-family house (Akhatova and Kranzl 2022). The uptake of retrofitting solutions at the household-level considering the heterogeneity amongst households can be well addressed by the agent-based modelling approach (Du et al. 2022; Rai and Robinson 2015; Moglia, Podkalicka, et al. 2018; Akhatova, Kranzl, et al. 2022).

Agent-based modelling is known for its flexibility and capability to incorporate heterogeneity (Moglia, Podkalicka, et al. 2018; Bonabeau 2002; Rai and Henry 2016). Therefore, this method is chosen to evaluate the uptake of retrofitting in a neighbourhood by different building owners. Retrofitting decisions can be regarded as investment decisions of building owners. However, these decisions are not simple single-step and purely economic decisions that are usually depicted in diffusion models (Akhatova, Kranzl, et al. 2022). Instead multi-stage investment decision-making that incorporates the recent findings from social psychology is employed in the presented model. This model analyses the uptake of neighbourhood-level renovation depending on the type of building owners and the presence of an intermediary actor as a facilitator of the uptake. The model explores several scenarios as depicted in the conceptual framework of the model in Figure 5.

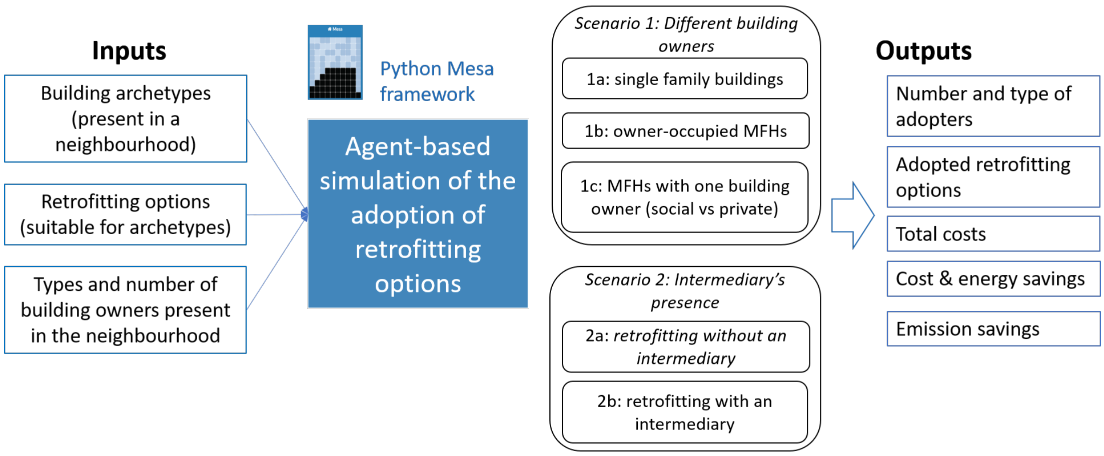

Figure 5: Modelling framework of the ABM of retrofitting adoption

As a default, the inputs of the model are the building archetypes according to TABULA (*TABULA WebTool* 2022), the relevant energy-efficient retrofitting packages consisting of insulation and installation of heat pump and PV, and the details about the floor area and types of building owners of a selected neighbourhood. The agents and their environment is initialised according to these inputs. As a result of agents' decisions whether to renovate or not, the model informs the modeller about the total number of adopters, the renovation packages that are preferred, total cost of retrofitting, as well as energy, economic and emission savings (Figure 5). For implementation of the model, the Mesa framework is used (Kazil et al. 2020).

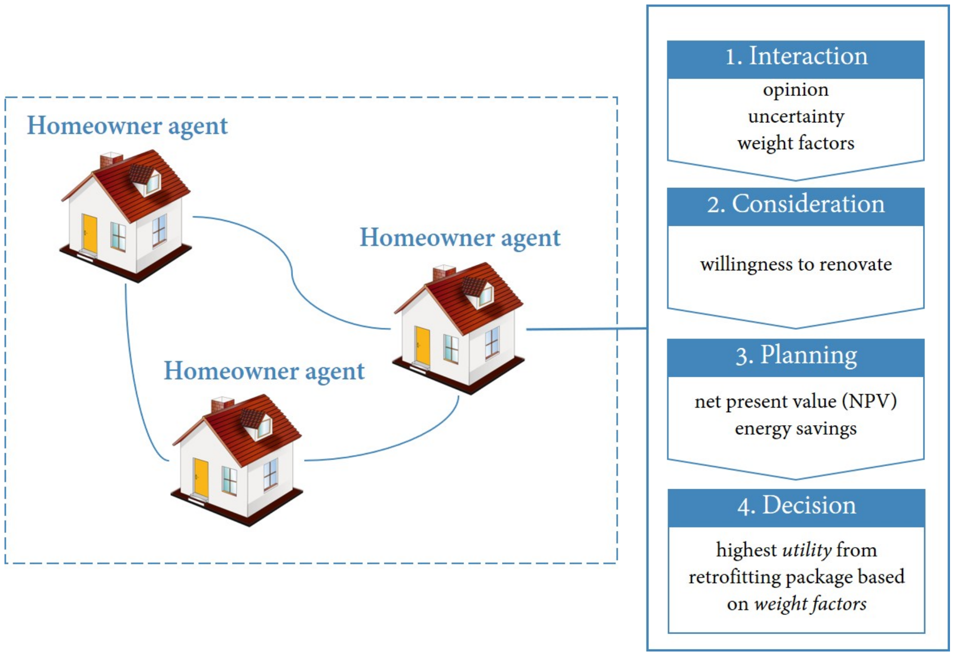

Figure 6: Agents and their decision-making stages

The key elements of the current agent-based model are the agents and their decision-making strategy. As shown in Figure 6, agents are homeowners that either own a single-family house or co-own a multi-family building (i.e. own a dwelling in a multi-family building). They undergo a multi-stage decision process as a result of is implemented as opposed to a simplified, one-off purchase decisions (Akhatova, Kranzl, et al. 2022; Arning et al. 2019; Busch et al. 2017) (see Figure 6). First, each agent interacts in a neighbourhood and adjusts its "opinion" and "uncertainty" according to the opinion dynamics model by Deffuant et al. 2002; Meadows and Cliff 2012. The "opinion" represents agent's attitude towards renovating and influences the willingness to renovate and the subsequent evaluation of the retrofitting packages (Rai and Robinson 2015; Friege 2016). Second, an agent is willing to renovate if the opinion is more positive (i.e. higher than 0.5 out of 1.0). Third, the agents who are willing to renovate move on to the next step where the retrofitting options are introduced to them and the agents calculate net present value (NPV) and the amount of heating demand reduction achieved by each retrofitting option as in Equations 3, 4. Based on the weights that each agent gives to economic (i.e. net present value of a retrofitting package) as opposed to environmental aspect (i.e. energy savings), a decision about the retrofitting option is taken. For example, an agent who assigns a larger weight towards the economic aspect tends to choose the most cost-efficient package. If none of the packages have a positive NPV, an agent will not adopt any of the retrofitting packages.

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{1+i^t}, \quad CF_t = E_0 * p_{g,t} - E_t * p_{e,t} \tag{3}$$

$$\Delta E = E_0 - E_t \tag{4}$$

t stands for a time period, i.e. a year, n for lifetime of renovation package, i for discount factor, CF_t for cash flow in each time period, including the initial investment costs $CF_0 = -I_0$ of a retrofitting package, and CF_t as in Equation 3. E_0 indicates the initial heating demand of a building, E_t is the heating demand after renovation package is implemented (both are assumed to be constant), $p_{g,t}$, $p_{e,t}$ stand for the retail prices of gas and electricity in corresponding time periods (It is assumed that as a result of renovation homes switch from initially gas heating to electricity).

In one time step, every agent goes through all the four stages. It represents three to six month-period of contacting the residents of a neighbourhood. After six such time steps indicating three years, a decision on neighbourhood-level renovation is taken and the outputs are calculated. More time steps can be simulated to see whether the neighbourhood renovation will come to an equilibrium. The flowchart of the simulation is depicted in Figure 7. Two main scenario groups are evaluated: variation of building ownership and the presence of intermediary. The first group of scenarios discusses to which extent making changes to building ownership will increase the willingness of agents to renovate. The second group of scenarios illustrates to which extent the intermediary actors can accelerate the rate of renovation in a neighbourhood.

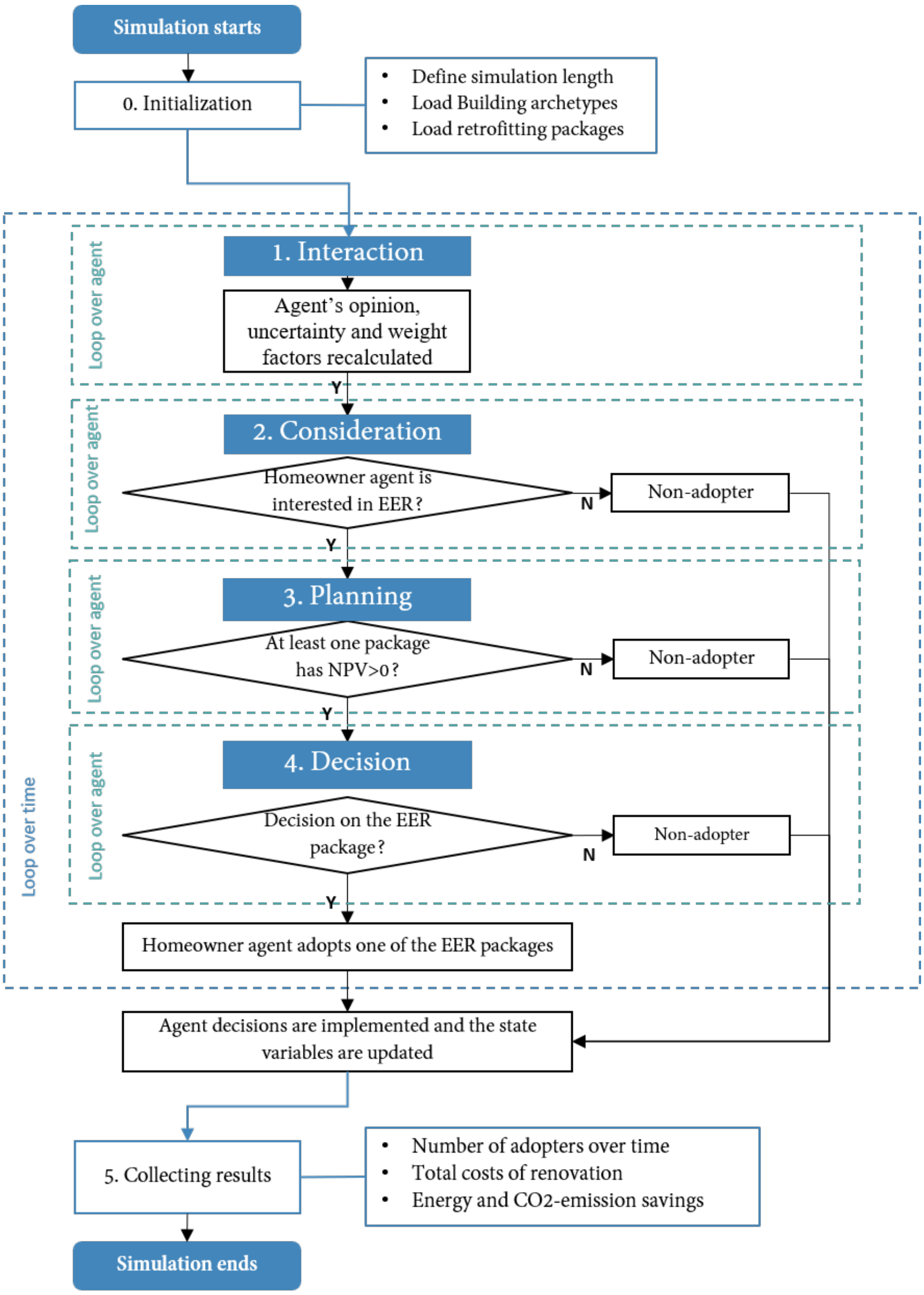

Figure 7: The simulation flowchart

The presented method of analysis allows to experiment with different investment behaviours (i.e. private landlord vs owner-occupiers), income distributions of homeowners, renovation subsidies, and the price of energy carriers (gas, electricity). Planning and implementing building retrofitting on a neighbourhood-scale puts a strong emphasis on the inclusiveness, i.e. that all owners are included in the process. Moreover, affordability of neighbourhood retrofitting measures can be ensured by reducing the costs via common purchase (i.e. economies of scale) and other innovative business models (see Akhatova and Kranzl 2022).

3.4 Evaluation of accessibility of EV charging infrastructure for understanding potential future demands

As we move towards transport electrification, deployment of charging infrastructure is widely seems as one of the first steps facilitating EV adoption, gaining a massive attention by governments around the world for the last years (Zhang and Fujimori 2020; Funcke and Bauknecht 2016). According to Castillo-Calzadilla et al. 2021 the inclusion of EVs is a promising solution towards achieving PED's goals.Therefore, understanding future demands for public EV charging infrastructure and deployment of accessible EV charging infrastructure plays one of the central roles in planning mobility infrastructure in PEDs. Accessibility has a wide range of meanings varying from definitions and applications (Levine 2020). The definition that relates to this study refers to accessibility as an indicator that "describes the location of an area with respect to opportunities, activities or resources that exist in other areas or in the same area" (Wegener et al.2020 cited in López et al. 2008).

Provision of accessibility for public charging infrastructure is essential for EV adoption to ensure equitable access to chargers, including those who do not have access to home charging. As many literature sources are focused on country- and city-level data in analysing EV charging infrastructure, this section describes a common method proposed for analysing the accessibility for EV charging points and future demands for chargers at a district scale. In addition, for identification of a disparity in access to EV charging points, the method suggests comparing districts within a city. The focus of the method is comparing accessibility indicators per postcode district (ZIP code).

There are four typical metrics for assessing public charging infrastructure such as the number of chargers, the number of chargers per square kilometer, the number of chargers per kilometer of road, and ratio of EVs per charger (Hall and Lutsey 2020). These metrics focus on normalizing public charging infrastructure by land or vehicle stock to monitor or measure progress toward infrastructure developments by time period and to identify infrastructure and policy gaps, using easy-to-access data. These metrics do not distinguish types of EV chargers and housing types, although they can impact different needs of EV drivers. For example, in terms of charging capacity types, fast DC chargers require less charging time and consequently can serve many more EVs per day than slow AC chargers. In terms of housing type, apartment buildings more likely will need more public charging points than single-family homes which have access to home charging (ibid).

In this study, accessibility indicators of EV charging points such as the number of EV charging points per postcode, charging capacity (kW), ratio of charging points per 10,000 population, and proportion of flats accommodation using gross floor area data are suggested to be assessed at a district level and compared across districts within a city using a linear regression model. Evaluation and comparison of these indicators between districts is used to identify the potential future needs for public EV charging points and social equity issues in terms of the deployment of EV charging points across districts. To forecast potential demand for public EV charging points across districts, the housing type indicator is used guided by he fact that it can impact the ability to charge at home. According to Hall and Lutsey 2020; Soylu et al. 2016, residents for apartment buildings typically 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.

Another indicator as EV charging capacity is suggested for assessing demand for public EV charging points across districts. An availability study of the different types of EV charging points can help to understand discrepancy between types of charging points among districts and offer solutions for future improvements. For example, this indicator can have a strong influence on perception of easiness and comfort of the charging solutions especially for EV drivers who do not have off-street parking and consequently can impact the EV adoption within a district. Therefore, the proposed method for evaluation of accessibility for public EV charging points at a district scale can be used as a tool for informing potential interventions towards the deployment of EV charging infrastructure at districts, including PEDs.

3.5 Model integration

To cover the whole planning transition process illustrated in Figure 1, the four PED modelling approaches previously described can be connected as shown in Figure 8.

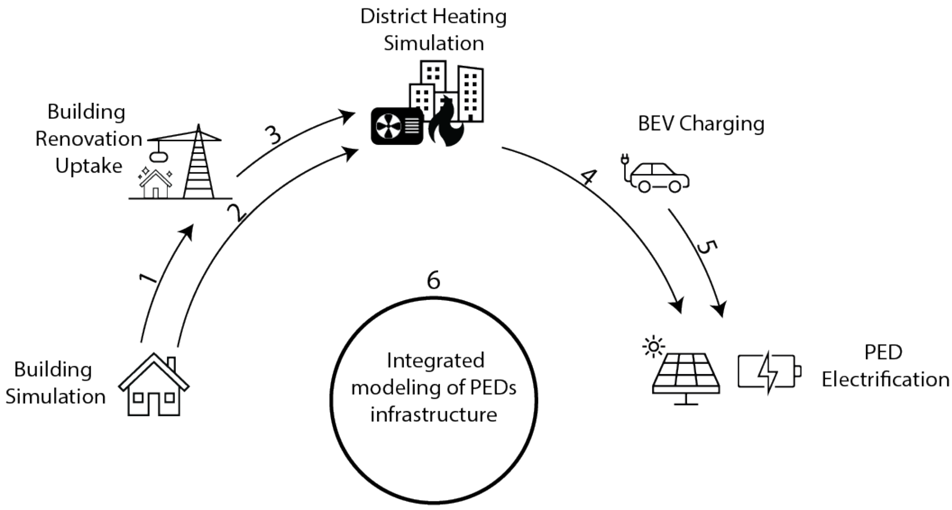

Figure 8: Integration of models and studies developed throughout the Smart-BEEjS project.

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 EV charging infrastructure
6	Optimal energy supply technology portfolio in the district

Table 2: Data inputs and outputs between the models (as depicted in Figure 8)

The authors use EnergyPlus to perform single building simulations in order to obtain data on energy performance and building renovation schemes. EnergyPlus provides the data in the form of annual specific useful space heating demand (kWh/m2/year) and provides information to calculate the NPV of energy renovations. The costs are calculated based on Koch et al. 2021. These data flow into the

Agent Based Modeling model and the District Heating Simulation (1). In the ABM, 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 District Heating Model utilises data from EnergyPlus to assess hourly heating demand (2). The ABM model 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 generates data regarding hourly total district heating demand which PEDso uses to assess the required infrastructure to cover it electrically (4). Assessment of the accessibility of Battery Electric Vehicle (BEV) charging results in the number of charging points in a district (5). This information feeds into the PEDso and is used to estimate the energy demand by EVs and their charging profiles in a district.

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 electric charging determine the optimal portfolio. Hence, several scenarios pathways are determined for achieving the PED status.

4 Discussion and Conclusion

This report describes methods developed within the Smart-BEEjS project and as part of the individual doctoral research. The methods developed support the planning of infrastructure requirements for transitioning towards PEDs and cover energy sectors such as electricity, district heating, building stock and electrified land transportation.

The overall contribution of this work is the creation and integration of techno-economic methods of analysis that together aim to facilitate the process of planning PEDs. In this way it is possible to determine the infrastructural changes needed to transform existing districts and neighbourhoods into PEDs. These methods focus on the most technically viable solutions at a district level, such as high and low-temperature district heating (Section 3.2), all-electric distributed energy supply from PV, heat pumps and storage system (Section 3.1), building energy retrofitting (Section 3.3), electric vehicles (Section 3.4). Together these methods can help to determine the pathways towards PEDs.

A literature review about neighbourhood energy systems modelling has revealed that existing models focus on the technical aspects of energy infrastructure. Instead it is becoming ever more important to ensure that implementation of new energy infrastructure should be aligned with principles of energy justice, such that the costs of energy transition do not fall on the most vulnerable in the society. Moreover, the existing works indicate the lack of methods that deal with problems specific to the needs of PEDs, such as the direct inclusion of a energy balance. Finally, more holistic and integrated approaches are necessary to account for sector coupling of the energy system.

The method for evaluation of accessibility of EV charging infrastructure in PEDs is also presented (Section 3.4). This method involves a consideration of the ratio of working population as well as the ratio of residents who do not have access to home charging, and charging capacity of EV infrastructure. Assessment of these indicators per districts shows the potential to evaluate the existing EV charging infrastructure and to be used for optimal planning of future EV charging needs. The method can aslo be used for identifying discrepancy in deployment of EV charging points among districts within a city by comparing indicators between districts to ensure that EV charging points are spread equally among districts. This method can be used as a tool for informing potential policy measures towards the deployment of charging infrastructure. Investigation of interaction effects between the number of EV charging points and availability of parking spaces is not in the scope of this study; however, this could be a promising area for future research.

The current report is the successor of the report 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 by the current WP4. The results of the modelling exercise on a pre-determined set of socio-technical context is provided in the D4.3 - Report on infrastructure requirements for developing sustainably PEDs, summarizing the outcome of the techno-economic modelling activities by the WP4. Together, the activities within the WP4 of the Smat-BEEjS provide a consolidated knowledge about the techno-economic aspects and a way forward in PED-driven energy transition.

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