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Urban Digital Twins Empowering Energy Transition: Citizen-Driven Sustainable Urban Transformation towards Positive Energy Districts

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Abstract

Both citizens and authorities play a crucial role in the successful implementation of Positive Energy Districts (PEDs). However, the current public participation methods often fail to facilitate interactive knowledge production in the context of energy flexibilisation and PEDs for the citizens. To close this gap, the DigiTwins4PEDs project will use an innovative public participation process and further develop energy simulation tools using urban digital twins. These tools could address issues such as energy flexibility strategies, including demand-side management, sector coupling, and energy storage options, among others. To support the public participation process, the urban digital twin platform will be integrated into a living lab concept and implemented in different case study regions to co-design energy flexibilisation strategies with citizens. The ultimate goal is to deliver a best-practice catalogue and an action plan for other cities to implement a community-driven transition to PEDs.

1. Introduction

Cities play a pivotal role in climate change mitigation, with numerous global urban centres committing to sustainable transitions through proactive green strategies. Europe has set an ambitious goal for successfully realising Positive Energy Districts (PEDs) by 2025 and 100 Climate-Neutral Cities by 2030 as part of the EU SET Plan[1]. This concerted effort urges city officials to deviate from conventional urban energy management practices and embrace developing policies and regulations that support the implementation of PEDs. This includes setting targets for carbon neutrality, establishing zoning regulations that encourage energy-efficient building designs, and creating incentives for renewable energy deployment within districts. The success of implementing such policies and bringing the PED concept to fruition relies not solely on technological advancements but also on fostering social, political, and business commitments (European Commission, 2020). Additionally, transitioning the energy system towards an energy producer model also involves empowering individuals and transitioning citizens from their traditional role as consumers to more active participants. This shift signifies a fundamental change in how communities engage with and contribute to their energy needs, fostering greater ownership and responsibility among citizens for creating sustainable and resilient energy futures. However, involving citizens in the planning and execution of PEDs has consistently emerged as a pivotal challenge and obstacle in PED project implementation (Bossi et al., 2020).

Citizens currently feel marginalised in the decision-making process regarding the energy transition of their district. (Massey et al., 2018) identifies several hurdles involving local communities in the energy transition. Initially, a significant challenge stems from the limited involvement of citizens and local organisations in this transition, exacerbated by communication gaps between government entities and the community. Secondly, the absence of adequate infrastructure to ensure transparency in policies and sustained community involvement presents a significant barrier. Thirdly, there is a notable lack of public trust in emerging energy technologies and apprehensions regarding adaptability. Fourthly, there is a deficiency in citizens' knowledge concerning technical aspects and policy matters. Finally, the absence of a structured model for community engagement complicates implementation efforts. The involvement of local communities in the urban design process is well-established; however, its role in energy transition remains highly under-explored. Despite different technological solutions already in place for green energy planning, the transition to PEDs backed by the local communities is still a matter of concern. The existing public participation methods utilised by city officials to generate awareness related to clean energy transition amongst the citizens primarily rely on questionnaires, flyers and discussions, which often lack adequate information and elements that allow interactive knowledge production for citizens on the energy profiles and potential to PED transition of their district. This ultimately proves to be a significant bottleneck in achieving ambitious goals such as the EU goal of 100 PEDs deployment by 2025.

To address this gap, DigiTwins4PEDs aims to employ an innovative public participation process embedded in a living lab concept across its four case study areas - Stuttgart (Germany), Vienna (Austria), Rotterdam (Netherlands) and Wroclaw (Poland), empowering their local community to push forward the energy transition of their district and make more informed decisions. This initiative seeks to utilise the urban digital twin framework to model, simulate, visualise and, most importantly, engage the local community in co-creating PED with the city officials. In this context, living labs will operate as intermediaries among citizens, research organisations, companies and city officials to evaluate the potential of using urban digital twins as a collaborative tool to co-create PEDs. Against this backdrop, this article offers initial insights into the ongoing research and planned technical advancements of the DigiTwins4PEDs project. DigiTwins4PEDs (2023-2026) is a transnational EU project with seven project partners and two cooperation partners.

[1] https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan

2. State of Art

The DigiTwins4PEDs project will use urban digital twin, which is a unified visual interface of integrated information (both spatial and non-spatial, both static physical urban objects and dynamic urban processes), to develop advanced geospatial applications and tackle technical, spatial, regulatory, legal, financial, environmental, social and economic aspects needed to establish PEDs. Urban digital twins are digital representations of the real-world built environment at the urban scale, but with the granularity that reaches the single building level (or sometimes even finer, depending on available data). Semantic 3D city models, a fundamental building block to developing an urban digital twin, are already available and accessible for all the project case study regions (except for Wroclaw). All semantic 3D city models are based on the international and open standard CityGML by the Open Geospatial Consortium (OGC). CityGML datasets store the geometry and semantics of common city objects such as buildings, trees, roads, and land use commonly found in real-world built environments. In the context of the current article, CityGML based 3D city models have been regularly used in the realms of sustainable urban development (Rahman et al., 2024).

(Eicker et al., 2018) utilised CityGML building models for the entire county of Ludwigsburg, Germany, to assess heating and electricity demands for each building in the current state and under ”Medium” and ”Advanced” refurbishment scenarios using SimStadt. Rooftop photovoltaic (PV) potential and carbon emissions were also analysed based on energy consumption and emission factors. Furthermore, it enhances the capabilities of the CityGML model to cope with energy-related data and to be better coupled with energy-simulation tools; in the past years, Energy Application Domain Extension (Energy ADE) has been developed as an extension to the CityGML standard. Energy ADE aims to define a standardised data model to allow for data storage, interoperability and seamless data exchange between 3D city models (based on the CityGML standard) and heterogeneous energy simulation tools (SimStadt, CitySim, etc.) and applications. Version 1.0 was released in 2018 (Agugiaro et al., 2018) and has been used in several projects and applications related to the calculation of energy demands (Rosser et al., 2019) and carbon emission profiles (Rossknecht and Airaksinen, 2020) of building stocks. However, its integration in the context of participatory energy planning and PEDs is new and needs further exploration and improvement. So far, Energy ADE represents the best candidate and most obvious option to enrich the urban digital twin capabilities in the context of the DigiTwins4PEDs project. Inspired by the concept of Energy ADE, a recent JPI Urban Europe project IN-SOURCE (”INtegrated analysis and modelling for the management of sustainable urban food water energy ReSOURCEs”) developed a Food-Water-Energy (FWE) ADE data model to study the nexus of food, water and energy systems (Padsala et al., 2021). Within IN-SOURCE, different renewable potential workflows such as photovoltaic potential (roofs, façade and open field) (Bao et al., 2023), bio-energy (Bao et al., 2020), AgriPV (Bao et al., 2022) and energy recovery from food and water waste (Braun et al., 2021) were developed in SimStadt and successfully tested using FWE ADE enriched CityGML building and landuse model of the entire district of Ludwigsburg in Germany. In a different JPI Urban Europe project, SUNEX (”Sustainable Urban food water energy NEXus”), the energy demand model MAED-City (Model for evaluation of energy demand of City) was adapted and used to project future long-term final energy demand of the cities Vienna, Berlin, Bristol and Doha. Based on MAED-City, the rapid assessment tool MAPED (Model for Energy Analysis of Positive Energy District) was further developed to analyse and evaluate the energy demand-supply of urban districts and test different scenarios and implementation measures for PED transformation. Based on indicators, MAPED successfully identified urban typologies that can be transformed into PEDs (Neumann et al., 2021). While SimStadt uses a CityGML-based building model to simulate and visualise energy demand and potential at a building scale on a temporal basis, MAPED allows for comprehensive analysis and evaluation of energy demand and supply scenarios at a district scale. Thus, combining SimStadt with MAPED could be interesting as it can allow for testing and evaluating different ”what-if” scenarios related to PED implementation strategy at various spatio-temporal scales. Regarding energy storage, recent developments in the urban digital twin platform for mobility have allowed the inclusion of dynamic processes such as traffic movement or changing traffic signals from the microscopic traffic simulation tool SUMO alongside 3D city models (Beil et al., 2020). Extending such development in the DigiTwins4PEDs project will allow for modelling electric vehicles as hybrid moving energy storage options and studying the interaction of building and mobility as an additional energy flexibilisation option.

Analysis and simulations are crucial for assessing PED feasibility. However, to achieve the DigiTwins4PEDs project goal of community-led PED transformation, it is also vital that citizens and city officials can visualise and grasp various options for energy flexibility and energy storage along with the socio-economic ramifications across different spatio-temporal scales. In the context of public participation, urban digital twins are often seen as vital data-sharing and virtual meeting points for urban stakeholder engagement. The creation of a 3D city model-driven public participation platform, piloted and applied in the redevelopment of Stuttgart’s Weilimdorf area, serves as a notable example (Würstle et al., 2021). This platform’s deployment in a real-world public participation initiative demonstrates its practical application. Furthermore, while facilitating the Weilimdorf redevelopment process, the platform also surveyed citizen attitudes towards such technological tools, with the majority expressing support for their use in local community engagement. Therefore, based on the purpose, an urban digital twins platform for PED could be developed as an information-sharing, gathering and/or co-designing platform for citizens and city officials to simulate and visualise different future PED implementation scenarios before its real-world implementations.

Web globes and frameworks such as Cesium, Esri (ArcGIS JavaScript API), and Mapbox (Mapbox GL JS) are commonly utilised to develop urban digital twin platforms on the front end. These platforms can interact with and visualise large-scale 3D city models stored according to OGC standards of 3D Tiles and i3S. On the backend, OGC has long offered a standardised and refined framework for various web services. These include the Catalogue Service, Web Feature Service (WFS), Web Coverage Service (WCS), Web Mapping Service (WMS), Web Processing Service (WPS), as well as the OGC Sensor Web Enablement Initiative (SWE). In 2017, drawing from insights provided by the OGC API Whitepaper [2], a novel approach emerged, prioritising web-centricity, user-friendliness for developers, lightweight specification development, and a transition from service-oriented to resource-oriented models. This evolution entailed the creation of modular specifications,

[2] https://docs.ogc.org/wp/16-019r4/16-019r4.html

comprising core and extension specifications, designed to facilitate straightforward implementation and widespread adoption, thereby marking the new era of OGC API. These standards build upon the groundwork established by existing OGC Web Service Standards (such as WMS, WFS, WCS, WPS, etc.) and serve as a critical building block for creating innovative APIs tailored for web-based access to geospatial content. (Santhanavanich et al., 2023) can be seen as a good example of how the new generation of OGC APIs, in particular 3D GeoVolumes, Processes and Features, were used in the backend to develop a web-based urban digital twin application that can not only simulate the building stock energy demand but also visualise the simulation results by integrating them back to the CityGML based 3D city models on-the-fly. Such a development can help non-simulation experts, such as citizens, to gain insights and visually comprehend their buildings' energy demand and potential interactively, enabling them to make informed decisions.

3. Aim and Objectives

The DigiTwins4PEDs project aims to leverage urban digital twins to unite local communities and city officials on a single platform, facilitating the collaborative development of PEDs. While public participation in urban design is a longstanding practice, a knowledge gap exists concerning its application in sustainable energy planning. To address this gap and innovate the public participation process, the DigiTwins4PEDs project draws inspiration from the capabilities of urban digital twins alongside seeking technological advancements. The objectives of the DigiTwins4PEDs project are as follows:

1. Employing a bottom-up approach, utilising 3D city models to intricately model urban energy systems and their flexibility strategies. Incorporating socio-economic parameters, this initiative aims to develop planning and simulation tools that aid citizens and urban stakeholders in identifying and visualising current and future energy demand, potential, and flexibility strategies within their district.

2. To develop new data-driven methodologies for identifying urban typologies within existing urban districts with significant potential for its transition to PEDs.

3. Developing and implementing an urban digital twin framework across various case study areas to facilitate an innovative public participatory living lab process to address the multifaceted aspects essential for establishing PEDs co-created by citizens and city officials.

4. To enhance the efficacy of PED initiatives, analyse diverse urban challenges through case studies, foster capacity building, facilitate knowledge transfer, and promote the adoption of best practices. By leveraging these insights, the aim is to improve the transferability of project outcomes to various urban areas within the EU and globally. The objective also aims to assess the impact of the DigiTwins4PEDs project on the accessibility and utilisation of energy subsidies provided by city officials.

In pursuit of its objectives, the DigiTwins4PEDs project seeks to answer the following key research questions:

1. How can urban digital twins enhance public participation in the sustainable energy planning process at the district level?

2. What are the potential challenges and opportunities associated with adopting urban digital twins to facilitate public participation in sustainable energy planning for districts?

3. What factors influence community engagement and collaboration with city officials in creating Sustainable Energy Districts using urban digital twins?

4. Methodology

The overall strategy of the DigiTwins4PEDs project is shown in Fig. 1, available in the appendix of this article. In a transdisciplinary co-working process, a framework to stimulate citizens' approach towards sustainable clean energy transformation of their communities will be developed. Citizen-driven actions require support at the urban policy level to be integrated into sustainable urban development in the long term. Therefore, in the DigiTwins4PEDs project, the city officials are integrated into the research process in a moderating role. The project follows two overarching methodological approaches: 1. Mapping and analysis: urban digital twins are used to identify urban typologies in an urban district that can potentially become PEDs. Both the technical feasibility and the readiness of the urban society for change/transformation are analysed based on socio-demographic and techno-economic data. 2. Implementation of living labs: the developed urban digital twin platform will be tested on-site co-creatively with citizens. The urban digital twin platform provides information and enables surveys and visualisation supporting simulations of different energy flexibility scenarios. The success factor will be evaluated using questionnaires and surveys on using urban digital twins. The co-working process is divided into three phases: co-design, co-creation, and co-learning. To realise the potential transformation of existing city districts into PED, active engagement of the local community and flexibility in the energy system are imperative. However, persistent challenges exist on both the energy demand and supply fronts. Addressing these challenges necessitates crucial measures, including community engagement through incentives and awareness-raising initiatives. To achieve this, strategies for interdisciplinary co-design phases involving citizens will be developed within the living lab context. The co-designed energy flexibilisation strategy and scenarios will be a basis for developing the urban digital platform.

On the backend of the urban digital twin platform, CityGML will be used as the base data model to store 3D building models, and its extension, Energy ADE, will be used to store all the building's energy-related semantics and attributes. Currently, the Energy ADE is extended further to accommodate spatio-temporal datasets on energy potential, demand and storage for its further use in simulating different energy flexibility scenarios, including demand-side management, sector coupling, energy storage profiles, amongst others. The vanilla CityGML dataset enriched with information from Energy ADE will be stored in a central database powered by 3DCityDB placed on top of PostgreSQL. This central database will be a data exchange platform between SimStadt and MAPED. SimStadt offers a granular approach using CityGML building models to simulate and visually represent energy demand, load profiles and potential at a building scale over time. Meanwhile, MAPED facilitates thorough analysis and assessment of energy demand and supply scenarios at the district level. Therefore, two-way communication between SimStadt and MAPED using Energy ADE will be established to evaluate energy flexibility scenarios at various spatial-temporal scales and to identify and evaluate different urban typologies for their transformative potential to PEDs. Such functionality will allow the local community to visualise their buildings' energy profiles and understand its impact on the energy scenario collectively at a district level. The primary objective of this integrated approach is to identify urban typologies showing characteristics conducive to becoming PEDs, such as high renewable energy potential, efficient energy usage, and adaptable infrastructure. Both SimStadt and MAPED will be supported by two additional databases - one containing useful socio-economic and demographic information and the second database acting as a look-up table for different building archetypes based on the TABULA Episcope project for European buildings [3]. These backend developments will then be integrated into a web-based urban digital twin platform for co-creation in the PED planning process and tested with the local community in a living lab format. The framework of CesiumJS will be used to develop the web client. The delivery of 3D city models on the web client as 3D tiles, the simulation results of different energy profile scenarios, and their visualisation will be based on the new generation of OGC APIs - 3D GeoVolumes and Processes, respectively.

Ultimately, the urban digital twin platform will facilitate citizens' informed decision-making through surveys and visualisation of different energy demand/production profiles, estimating carbon reduction in their buildings and districts based on various climatic, refurbishment, and energy flexibility scenarios. The feedback from the living labs will be used to optimise the urban digital twin platform iteratively. The results will be shared with the local community and the project partners in a co-learning phase following a P2P learning process and will be published as part of a best practice catalogue at the end of the project.

5. Case Studies

The DigiTwins4PEDs project aims to test its approaches on the case study regions of Stuttgart (Germany), Vienna (Austria), Rotterdam (Netherlands), and Wroclaw (Poland).

5.1 Stuttgart

The case study in Stuttgart will focus on the Nordbahnhofviertel district, which faces urban, infrastructure and societal challenges due to adjoining constructions of Stuttgart 21 and Rosensteinviertel. In addition to infrastructure and societal development, it becomes essential for Nordbahnhofviertel to develop itself in terms of energy infrastructure with Stuttgart 21 and Rosensteinviertel. Thus, its energetic transformation to PEDs can help Nordbahnhofviertel to ensure that it is no longer insular and ensure a sustainable basis of life for its current and future residents.

5.2 Vienna

The case study in Vienna will focus on the project area "Grätzl 20 + 2" as a part of the WieNeu+ urban renewal programme of the city of Vienna. Grätzl 20 + 2 is located in the neighbouring 2nd and 20th district of Vienna and was launched in early 2023 as a cross-district programme in the districts of Brigittenau and Leopoldstadt. It combines the area in the 20th district up to the Danube Canal and Stromstrasse with the "Volkertviertel" and "Alliiertenviertel" neighbourhoods in the 2nd district, with Nordwestbahnstrasse connecting the two areas. A particular focus in these areas is to transform the currently gas-based energy supply system to alternative renewable energy sources and evaluate the implication of such conversion on the power and heat load management and related peak loads. Therefore, the intended approach within the DigiTwins4PEDs project is to co-design different district energy transformation scenarios with a focus on energy flexibilisation options using the simulation tools and co-create with residents and decision-makers to evaluate potentials and opportunities to transform the Grätzel 20+2 towards a PED.

[3] https://webtool.building-typology.eu/

5.3 Rotterdam

The case study in Rotterdam will focus on the districts of Het Lage Land and Prinsenland. Rotterdam is committed to finding future-proof solutions to reduce its carbon footprint and become carbon-neutral by 2050. However, the city will not be able to achieve its climate action pledge alone: input from the government, province, and industries such as the port, as well as changes in city residents' behaviour, will also be necessary. Within the DigiTwins4PEDs project, the districts of Het Lage Land and Prinsenland will be used as a test case to experiment with living labs and the development and evaluation of the urban digital twin platform for co-creation and community-based solutions to enable the local community to drive energetic transformation by information exchange, visualising future energy demand, potential, flexibility scenarios and its socio-economic impact at a community level. The City of Rotterdam has already established a "Digital City Rotterdam" to improve the efficiency of urban planning and management. Connecting the Digital City Rotterdam with the activities and outputs of the DigiTwins4PEDs project will be a valuable opportunity to engage citizens in a co-creation process to start the transition towards PEDs.

5.4 Wroclaw

The case study in Wroclaw focuses on the district of Kleczków, which is facing infrastructural and societal challenges in connection with the implementation of "Nowe Kleczków" and the planned functional and spatial changes in the western and eastern parts of Kleczków. For the sustainable development of Kleczków, it is important that it continues to future-proof its energy infrastructure. Thus, its energetic transformation to PED can provide sustainable living conditions for its current and future residents. A CityGML based 3D city model is currently under development for the case study area.

6. Conclusion

The DigiTwins4PEDs project facilitates the interdisciplinary exchange between science, local communities and politics. The project presents representative case studies for PED flexibilisation and can thus be transferred to other urban development projects within the EU and beyond. The DigiTwins4PEDs project chooses a bottom-up approach to enable civil society to drive the transformation of their district towards PEDs. In this process, the DigiTwins4PEDs project, with the citizens and city officials, will identify barriers preventing the progress of PEDs and energy flexibilities within local communities. To close these gaps, DigiTwins4PEDs will use and evaluate urban digital twins in co-creating PEDs with citizens to address social and technical issues inclusive of accelerating the energy transitions of dense urban areas to PEDs and studying its impact on a local scale (building, district and city) beside regional one. In addition, for social, legal, regulatory and technical implications, urban digital twins as a co-creation platform for citizens and city officials will allow them to simulate and visualise different energy transition scenarios before their real-world implementation. This will help monitor the expected performance and sustainability of case study areas using metrics such as urban energy demands by end-use, renewable energy potentials and supply, energy flexibility, storage and PED interaction with the district and regional energy systems besides reduction of carbon emissions. Through workshops and dissemination activities, the research results will be transferred to the government, civic society groups, communities, and businesses that share the same goals. Lastly, based on the project findings, a best practice catalogue and visualisation toolkit will be publicly available for further replication in other European and global cities.

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Website: https://digitwins4peds.eu/

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A. Appendix

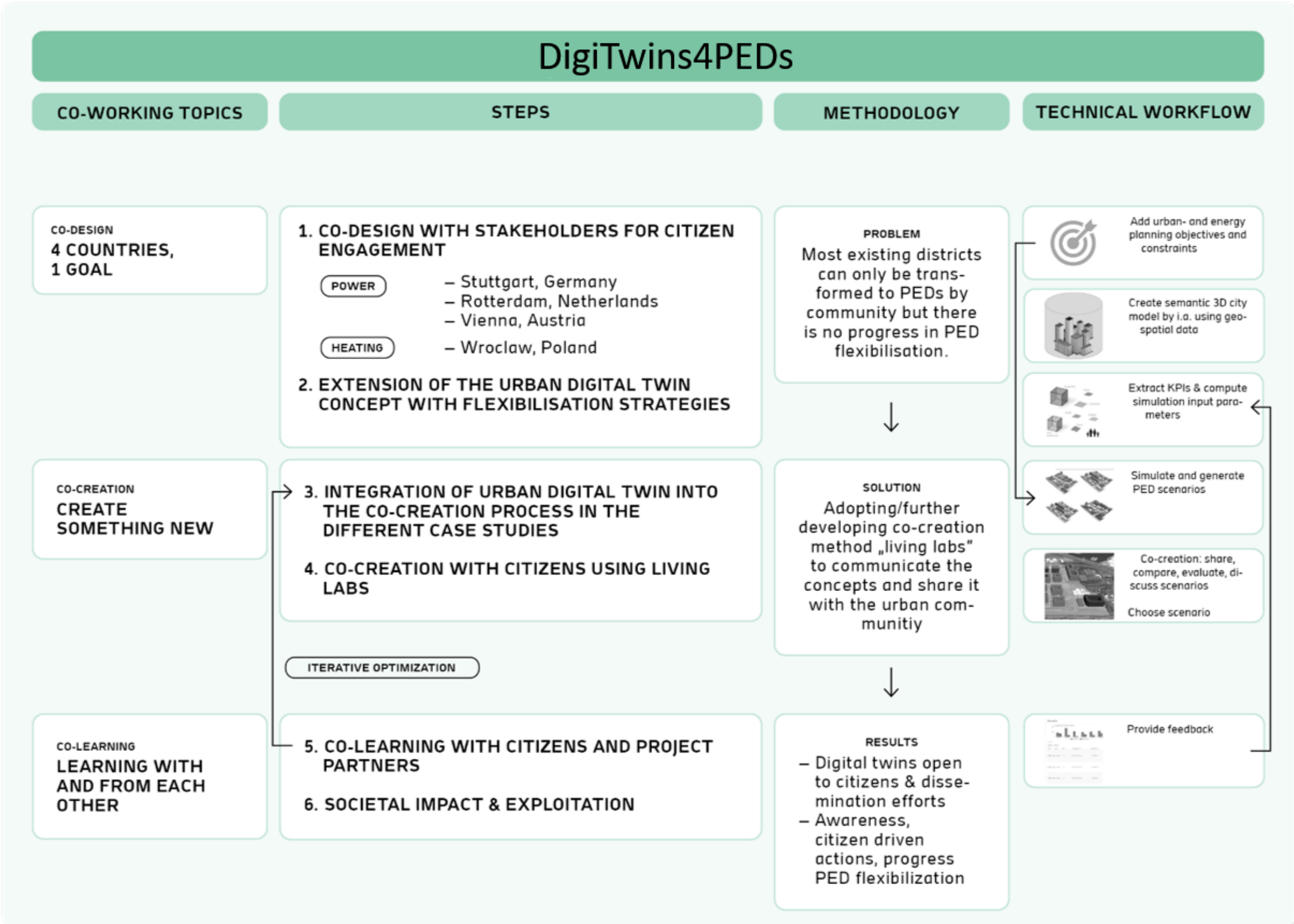

Figure 1. Overall strategy of the DigiTwins4PEDs project