Research Article/ Review Article/ Perspective Article (Remove where relevant)

Digital Twin for Positive Energy Districts: A Web-Based Viewer for Scenario Simulation of the mixed-use area Jättesten, Gothenburg

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Abstract (250 words) Style Name

This research presents a web-based Digital Twin (DT) platform, DT4PED, developed to support the progression toward Positive Energy Districts (PEDs) through integrated modeling, simulation, and visualization capabilities. PEDs, as defined, represent urban areas that aim for net-positive energy performance by harmonizing local energy consumption with on-site renewable energy generation. DT4PED functions as a decision-support tool, amalgamating urban datasets with parametric modeling to assist municipal authorities, urban planners, and facility managers. The platform integrates Grasshopper scripting with EnergyPlus for granular, building-level energy simulations and leverages UrbanOpt for broader, district-level analyses. The interactive web viewer, developed using Unreal Engine and deployed via Pixel Streaming, facilitates real-time visualization of simulation outcomes, comparative scenario analysis, and performance metric display, without necessitating specialized hardware or software installations on the user's side. This architecture endeavors to enhance accessibility and enable collaborative engagement among diverse stakeholders. The system is designed to model various interventions, including energy efficiency measures, the integration of renewable energy sources such as photovoltaics and battery storage, and demand-side management strategies. The Jättesten district in Gothenburg, Sweden, serves as the initial case study, demonstrating the platform's capacity for real-time scenario testing through interactive visualization and data-driven analytics. While acknowledging the need for further development concerning scalability, integration with existing urban platforms, and managing computational resource demands, this research underscores the potential of Digital Twins to bridge advanced computational modeling with practical energy planning in the context of PED development.

Keywords: Digital Twin, Positive Energy Districts, Energy Simulation, Urban Energy Planning

Highlights

- The DT4PED platform uniquely combines detailed energy simulations (EnergyPlus, UrbanOpt) with a high-fidelity, interactive 3D web viewer (Unreal Engine, Pixel Streaming) for visualizing and simulating Positive Energy Districts (PEDs).
- DT4PED enables users to dynamically create and test various PED scenarios, leveraging a scalable, containerized backend for reproducible and parallel simulations.
- The development prioritized stakeholder engagement and user experience (UX/UI), ensuring the platform is not only technologically robust but also accessible and valuable for real-world urban planning decisions.

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Cite this article:
Lastname, F. M., & Lastname, F. M. (Year). Title of the article. Title of the Journal, Volume 2025, Page range: 224-237

1 Introduction

Urban areas are undergoing a transformation in response to global climate targets, with increasing emphasis on energy-positive, resource-efficient, and citizen-inclusive development. Among the strategies driving this shift is the concept of Positive Energy Districts (PEDs)—urban areas that balance local energy consumption with on-site renewable production and achieve net-positive energy performance over the course of a year. As recognized in several European policy initiatives, PEDs require a shift from isolated building interventions to systemic, neighborhood-scale planning approaches that address technical, environmental, and social dimensions simultaneously.

This shift places new demands on planning tools and data infrastructures. Designing and evaluating PEDs involves navigating complex interdependencies across buildings, energy systems, stakeholders, and regulatory frameworks. Conventional energy modeling tools, while technically robust, often lack the capacity for integration across scales and domains, and tend to be inaccessible to non-expert stakeholders. Moreover, urban energy systems are increasingly dynamic—characterized by real-time interactions between distributed generation, flexible loads, and digital controls—further challenging static modeling and planning practices.

In this context, digital twins are emerging as a promising paradigm for urban energy planning. Defined as dynamic virtual representations of physical systems that are continuously informed by data, digital twins provide a framework for simulation, visualization, and stakeholder engagement. In the urban domain, they offer the potential to link detailed energy models with spatial interfaces, making complex information more actionable for both technical and non-technical users. While digital twins have seen widespread adoption in manufacturing and asset management, their application to PED planning remains underexplored, particularly at the district scale.

This paper responds to these gaps by presenting Digital Twin for PED (DT4PED), a proof-of-concept digital twin platform developed for the Jättesten district in Gothenburg, Sweden as the first case study. The system integrates containerized backend simulations using URBANopt and EnergyPlus with a web-based 3D viewer built in Unreal Engine. The DT4PED platform allows users to define, simulate, and visualize PED scenarios through an interactive interface accessible via standard web browsers. The platform supports key planning functionalities, including the evaluation of energy efficiency measures, renewable integration, and operational flexibility at the district scale.

Through a structured methodology combining PED systems modeling, urban digital twin architecture, and UX/UI co-design, the study advances the state of the art in scenario-based PED planning tools. In addition to developing the technical architecture, we also conducted a stakeholder-driven UX/UI evaluation with six organizations to assess usability, perceived value, and interface clarity. This dual focus on simulation fidelity and participatory functionality positions DT4PED as a scalable and transferable framework for future PED initiatives.

The remainder of the paper is organized as follows: Section 2 reviews relevant literature on digital twins, energy simulation tools, and urban visualization interfaces. Section 3 outlines the methodological framework used to develop the digital twin. Section 4 presents the design process and system architecture, followed by stakeholder evaluation results in Section 5. Finally, Section 6 discusses the broader implications of the work and outlines pathways for future development.

2 Background and Related works

2.1 Digital Twins for Urban Energy Systems and Sustainable Districts

Digital twin (DT) technologies have evolved from their origins in aerospace and manufacturing to play an increasingly pivotal role in urban sustainability and energy planning. A digital twin is commonly defined as a dynamic virtual representation of a physical system, updated continuously with real-world data and capable of simulating physical processes (Boje, 2020). In urban contexts, this translates to interactive 3D models that integrate data streams such as sensor inputs, weather conditions, and operational parameters to replicate and predict urban infrastructure behavior. Their application in the energy domain is particularly promising given the need to manage complex, interconnected systems across buildings, grids, and mobility networks (Lu, 2020).

As cities transition toward climate-neutral and energy-positive development pathways, urban digital twins (UDTs) have emerged as critical tools for integrating multi-domain data into coherent, decision-support environments. Recent literature highlights the growing importance of Urban Multi-Energy Systems (UMES)—where electricity, heating, cooling, and transport infrastructures are tightly coupled—and the challenges these systems pose in terms of planning, coordination, and stakeholder governance (Heendeniya, 2020). Digital twins offer a means to operationalize such complexity by enabling system-wide simulations, data-driven monitoring, and scenario-based assessments across the lifecycle of urban districts, from early design to long-term operation and retrofit (Coors, 2023). This approach is particularly relevant to the development of PEDs, which require both anticipatory planning and real-time coordination. PEDs are defined as urban areas that achieve net-zero annual energy import and greenhouse gas emissions through localized renewable energy production, energy efficiency measures, and demand flexibility. Unlike individual net-zero buildings, PEDs operate at a community scale and leverage system synergies (JPI Urban Europe, 2023). Digital twins are central to realizing this vision, providing a platform to simulate complex interactions among technical systems, users, and environmental conditions.

Furthermore, the implementation of PEDs is not only a technical challenge but a socio-institutional one. Conventional planning tools often fail to facilitate meaningful stakeholder engagement or interactive knowledge co-production (Voinov, 2010). Digital twins address this gap by offering visual, accessible, and participatory environments where diverse actors can collaboratively explore scenarios, interpret impacts, and co-create energy strategies. Early empirical evidence suggests that such platforms enhance stakeholder understanding and build consensus on sustainable interventions (Coors, 2023).

To structure this evolution, the development of digital twins for PEDs can be conceptualized as a three-phase progression:

1. *Digital Model (DM)* – a static representation built from real-world data and used for baseline scenario simulation. This corresponds with bottom-up Urban Building Energy Modeling (UBEM), using tools like EnergyPlus to estimate performance based on geospatial and typological data (Reinhart, 2016; Dogan, 2017).
2. *Decision Support Tool (DST)* – an enhanced model that incorporates user interaction, scenario management, and stakeholder feedback. This stage supports participatory planning and policy co-creation, positioning the digital twin as a collaborative interface (Kitchin, 2022).

3. *Full Digital Twin (DT)* – a real-time, interactive system integrating live data streams, predictive analytics, and control capabilities. This cyber-physical system supports continuous monitoring, smart grid coordination, and adaptive system response (Khajavi, 2021, Jacobsen, 2020).

Progressing from DM to DST to DT involves significant technical and institutional challenges, including data interoperability, semantic modeling, cybersecurity, and governance.

2.2 District-Scale Energy Modeling: URBANopt and EnergyPlus

A foundational element of any urban energy digital twin is a reliable engine for Urban Building Energy Modeling (UBEM)—the simulation of energy flows within and between buildings under varying operational and climatic conditions. EnergyPlus, developed by the U.S. Department of Energy, remains one of the most widely used and validated tools for this purpose, particularly at the building level. However, its original design for single-building simulations presents challenges for district-scale applications, where shared infrastructure and inter-building interactions—such as district heating or collective photovoltaics—must be considered (Reinhart, 2016). To address these limitations, the National Renewable Energy Laboratory (NREL) introduced URBANopt, an open-source platform tailored for simulating neighborhood-scale energy systems. Built as a modular software development kit (SDK), URBANopt orchestrates multiple EnergyPlus and OpenStudio models simultaneously, enabling the simulation of building clusters and shared assets such as energy storage and thermal networks (Macumber, 2023).

URBANopt manages geospatial input data, automates simulation execution, and aggregates performance metrics at the district level. Its architecture is extensible, supporting integration with other engines (e.g., Modelica for thermal networks), allowing for advanced and hybrid modeling workflows. Evaluations of UBEM tools highlight URBANopt's strength in maintaining consistent physics and system-level accounting across diverse building types (Cerezo Davila, 2017). However, this rigor can lead to longer computation times as model scale increases. To mitigate this, many studies adopt hybrid approaches, combining detailed simulations for representative buildings with simplified models for others to balance accuracy and efficiency (Dogan, 2017). In summary, URBANopt offers a scalable and coherent modeling framework for digital twins, well-suited to the simulation needs of PEDs by capturing both individual building dynamics and neighborhood-level energy interactions.

2.3 3D Web-Based Visualization with Game Engines

While robust simulation engines underpin the analytical capacity of digital twins, their effectiveness in urban planning contexts depends significantly on the design and accessibility of their user interfaces and visualization environments. Particularly when used in participatory settings, digital twins must translate complex energy data into intuitive, spatially meaningful representations that are accessible to both experts and non-experts alike.

Recent advances in game engine technologies, notably Unreal Engine and Unity, have enabled the real-time rendering of high-fidelity 3D urban environments. These platforms have been widely adopted in smart city applications—from traffic simulation to public space design—due to their ability to handle large spatial datasets, apply photorealistic rendering, and simulate dynamic lighting and environmental conditions (Fox, 2022). In the energy planning domain, such visual realism helps stakeholders better understand planning scenarios by contextualizing simulation results within familiar urban settings. For instance, overlaying performance indicators directly on 3D building models enhances interpretability compared to abstract charts or tables.

However, rendering complex 3D scenes can impose significant performance constraints, especially for users without specialized hardware. To address this, the use of web-based pixel streaming has emerged as a scalable solution. Introduced in Unreal Engine 4.21, pixel streaming offloads rendering to a server and transmits video frames to the user's browser, while capturing real-time input for bidirectional interaction. This approach enables high-quality, interactive 3D content to be accessed from standard devices without software installation, thus broadening accessibility and enabling remote collaboration (Epic Games, 2023).

Pixel streaming has proven effective in use cases such as architectural walkthroughs and interactive dashboards, and its application in urban digital twins enhances stakeholder engagement by supporting direct manipulation of scenarios—such as toggling energy layers, selecting buildings, or adjusting timeframes. This level of interactivity supports participatory planning, allowing users to explore, question, and co-create solutions. Despite its potential, many current digital planning platforms still suffer from limited flexibility and pre-defined scenario structures, restricting opportunities for active user contribution (Kitchin, 2022; Coors, 2023).

In the context of PEDs, such immersive and responsive 3D interfaces play a crucial role in bridging analytical rigor with visual storytelling. By embedding simulation outcomes in a spatial context, digital twins facilitate more informed dialogue and decision-making—particularly in workshops, public consultations, and co-design settings aimed at inclusive and sustainable urban transitions.

2.4 Stakeholder Participation and UI Design Considerations

For digital twin tools to be effective in real-world urban planning, careful attention must be paid to user interface (UI) and user experience (UX) design, as well as the broader participatory process (Mazzetto, 2024). A recurring lesson in the literature is that technology alone cannot guarantee stakeholder involvement; the tools must be designed around the users' needs and capacities (Malakhatka, 2025). In land-use and energy planning, stakeholders range from technical experts (who desire detailed data and fine control over model parameters) to citizens and public officials (who need simplified views and clear insights). Crafting a UI that serves both ends of this spectrum is non-trivial. Prior research suggests adopting a *co-creation* approach: involve end-users early in defining what functionalities and visualizations they find useful. This design is in line with emerging principles of "human-centered" urban digital twins. where the focus is on improving human collaboration and decision-making rather than just showcasing technology.

The background and related work highlight that **(i)** digital twins are becoming essential to plan and manage positive-energy districts and energy communities, combining multi-domain data and fostering collaboration; **(ii)** advanced modeling tools like URBANopt and EnergyPlus provide the simulation muscle needed for accurate district energy analysis; **(iii)** game engines and web streaming technologies enable those analyses to be visualized and shared interactively in ways previously not possible; and **(iv)** placing stakeholders at the center of tool design and use is crucial for the success of digital planning platforms. Our research builds upon these insights to create a state-of-the-art PED digital twin for Jättesten, and pushes the envelope by tightly integrating the technical and participatory aspects. The next sections will detail our methodology for developing the digital twin (including data inputs, modeling approach, and system architecture), followed by results from scenario simulations and stakeholder feedback, and finally a discussion of the implications for PED planning and digital twin deployment in practice.

3 Methodology

This study adopts an interdisciplinary, multi-layered methodological framework to develop and test a DT4PED, with specific application to the Jättesten district in Gothenburg (Figure 1). The methodology is structured around the integration of three complementary domains: (1) PED system modeling, (2) Urban Digital Twin (UDT) architecture, and (3) UX/UI design and stakeholder interaction. These domains are developed iteratively through five core methodological stages, ensuring that the final system is simultaneously grounded in robust energy modeling, technically scalable, and socially accessible.

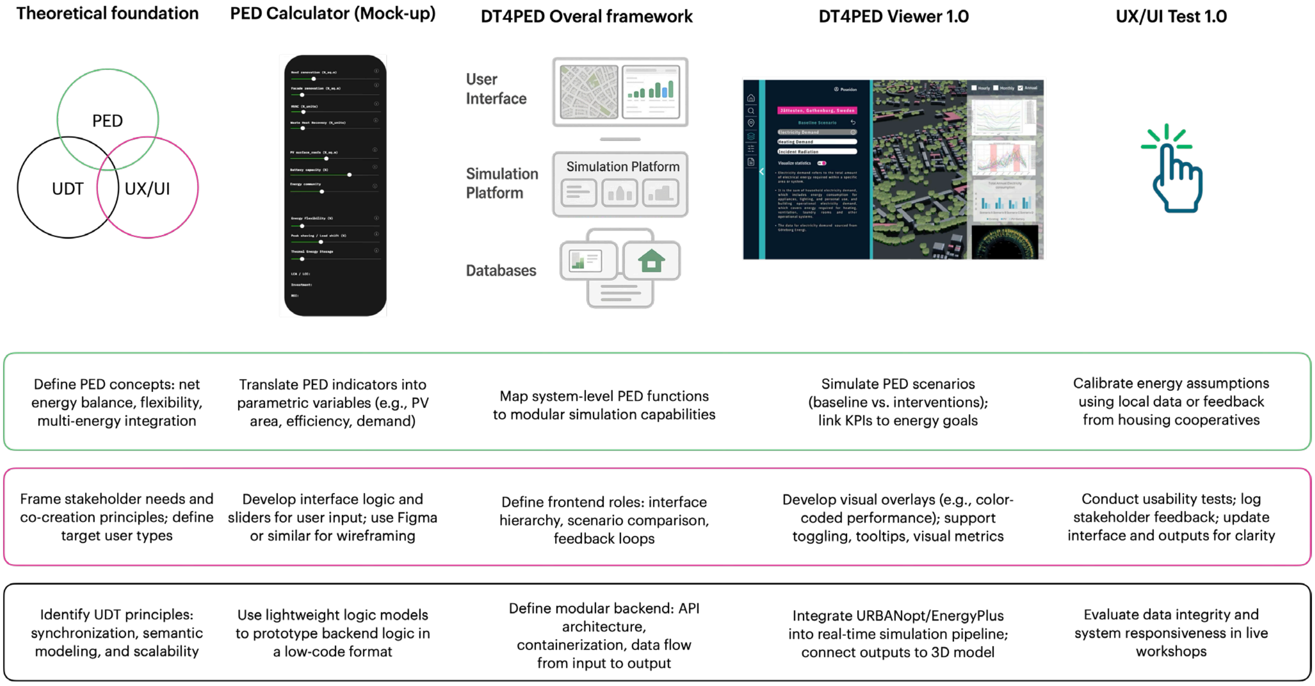

Figure 1. DT4PED overall methodology.

Stage 1: Theoretical Foundation

The first stage focuses on the theoretical underpinnings of PEDs, digital twins, and human-centered design. The PED framework adopted in this study aligns with the PED 3.0 concept promoted by the JPI Urban Europe and the European SET Plan (IWG 3.2. In parallel, the study incorporates digital twin principles from recent urban systems research, emphasizing dynamic data integration, model synchronization, and multi-domain interoperability. Finally, UX/UI methods are informed by participatory planning theory and stakeholder-centered co-design approaches (Voinov, 2010), ensuring that the platform addresses the needs of diverse users, including city officials, energy planners, and citizens.

Stage 2: PED Calculator Mock-Up

The second stage involves the development of a lightweight PED Calculator prototype, designed to translate high-level energy policy goals into a set of parametric input variables. These include building energy demand, photovoltaic (PV) surface area, system efficiency, flexibility measures, and battery storage capacity. This stage serves as a conceptual bridge between theoretical PED criteria and the logic required for simulation. To this end, the tool was implemented as a functional mock-up that visually represents trade-offs and user-selected scenario variables in an interactive format. The mock-up also allowed early testing of user interaction flows and backend logic in a low-code setting, following best practices in rapid prototyping and co-design (Norman, 2013; Wurzer, 2021).

Stage 3: DT4PED Framework Design

The third methodological phase consists of the architectural design of the DT4PED platform, structured in four tiers: *data layer, model and simulation layer, application layer and decision layer* (IBM, 2013). Scenario inputs—such as technology deployment or retrofit strategies—are compiled into structured input files (GeoJSON, IDF, osm) and processed through URBANopt's modular workflow. A containerized microservice architecture, orchestrated via Docker and Kubernetes, was developed to support parallelized scenario execution, improve computational reproducibility, and facilitate future scaling in cloud environments (Boettiger, 2015; Jacobsen, 2020). In terms of digital twin alignment, the system incorporates principles of semantic modeling and temporal synchronization, ensuring that each simulation run is uniquely identified, version-controlled, and traceable across user sessions. This approach is consistent with recent efforts to operationalize FAIR (Findable, Accessible, Interoperable, and Reusable) digital twin infrastructures in smart energy systems (Khajavi , 2021; Kitchin, 2022).

Stage 4: DT4PED Viewer Implementation

The fourth stage focuses on the development of the DT4PED Viewer, a fully functional digital twin interface designed to visualize simulation results and support user-defined scenario testing. The front-end is built using Unreal Engine, chosen for its high-fidelity 3D rendering and real-time interaction capabilities. The geometry of the Jättesten district was modeled in Rhino/Grasshopper and imported into Unreal Engine via Datasmith, with semantic metadata (e.g., building IDs, PV areas, usage types) preserved for simulation-result binding.

The Unreal application supports interactive scenario selection, performance visualization (e.g., energy balance, demand profiles), and time-series analytics. Simulation outputs from the backend (stored in structured JSON and CSV formats) are mapped to their corresponding 3D building models using persistent identifiers, enabling visual overlays, tooltips, and KPI dashboards. To ensure wide accessibility, the application is hosted on a GPU-enabled server and deployed via Unreal Pixel Streaming, allowing users to access the tool through any modern web browser without needing high-end hardware (Epic Games, 2023). This interface design is informed by recent scholarship emphasizing the cognitive benefits of spatially embedded data visualization and the use of game engines in urban digital twin platforms (Fox, 2022).

Stage 5: UX/UI Test and Stakeholder Feedback

The final stage involves the evaluation of the DT4PED Viewer through structured stakeholder testing. This included a series of user experience (UX) sessions with six organizations (municipal planning departments, housing associations, architects, facility managers and utility providers), where participants interacted with the tool and provided feedback on Content & Information Design, Visual & Interface Design, Interaction & Usability, and Value & Usefulness. Qualitative feedback was collected through semi-structured interviews and direct observation, while interface performance was logged for debugging and optimization. This process enabled the refinement of user interface components, improved scenario workflows, and contributed to the alignment of simulation results with stakeholder expectations. The methodology follows human-centered design frameworks (ISO 9241-210) and builds on participatory modeling literature that emphasizes co-creation and system transparency in complex urban systems (Voinov, 2010, Innes, 2010).

4 Design process and preliminary results

4.1 DT4PED conceptual framework

The DT4PED conceptual framework illustrates a staged evolution from a static Digital Model (DM) to a dynamic Digital Twin (DT), structured across four interrelated layers: stakeholder, application, model, and data. The stakeholder layer captures the shifting roles of users—planners, residents, facility managers, and technology providers—as the system evolves. The application layer encompasses the platform’s functionalities. Initially, it supports scenario simulation for PED planning, including interventions in energy efficiency, flexibility, and renewable integration. In the DT stage, it adds real-time monitoring, optimization, and system control, transforming the platform into a decision-support and operational tool. The model layer provides analytical depth. Static modeling of buildings, systems, and materials defines the DM stage, while dynamic, real-time models—including thermal, electrical, and economic simulations—support continuous performance assessment and system responsiveness in the DT. The data layer underpins the system, beginning with static datasets (e.g., building archetypes, energy profiles) and evolving to include real-time sensor inputs, IoT data, and smart grid signals. This transition enables live simulation calibration and adaptive control. Together, these layers frame the DT4PED system as more than a visualization tool: it is a cyber-physical infrastructure that supports urban energy transitions through scalable modeling, stakeholder engagement, and real-time analytics. The framework enables an iterative path from planning to operation, consistent with emerging PED and digital twin strategies in European urban innovation agendas.

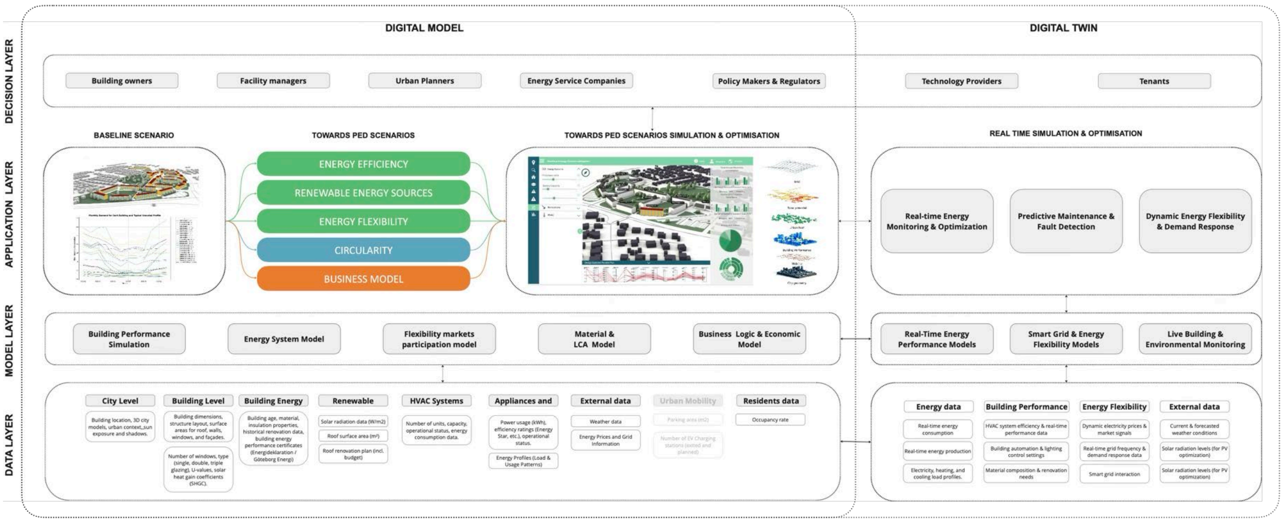

Figure 2. DT4PED conceptual framework

4.2 System architecture

The The system architecture of DT4PED has been designed to support real-time, user-driven scenario simulation and interactive 3D visualization for PED planning. It integrates a containerized backend for dynamic energy modeling with a web-based game engine frontend, providing an end-to-end framework that is both computationally scalable and accessible to a broad range of stakeholders.

4.2.1 Energy Simulation Backend

The backend uses containerized Kubernetes-based architecture, enabling on-demand simulations using EnergyPlus and URBANopt. It was developed through three iterative phases aimed at increasing user interactivity and computational flexibility:

- *Initial Phase – Predefined Simulations*: Early iterations relied on offline simulations configured in Grasshopper using Ladybug Tools. Experts defined a fixed set of scenarios, and results were visualized through a web interface. However, this static architecture limited user control and required manual re-computation for any changes.
- *Intermediate Phase – Parametric Transformations*: To enhance interactivity, selected parameters (e.g., PV system size coverage and configuration) were made adjustable via calls to the PVGIS API applied to precomputed outputs. This allowed users to explore simple scenario changes without re-running simulations.
- *Current Phase – Fully Interactive Backend*: The latest architecture supports dynamic scenario creation, where users define input parameters (geometry, systems, operation) through the interface. These inputs are automatically translated into URBANopt-compatible files and submitted to a Kubernetes-orchestrated simulation environment. Simulations are run in isolated Docker containers, ensuring parallel processing, reproducibility, and scalability. Results are parsed, enriched, and returned for immediate visualization and analysis.

This setup eliminates the need for local installations and supports a multi-user environment, enabling planners and stakeholders to interactively test scenarios with high technical fidelity.

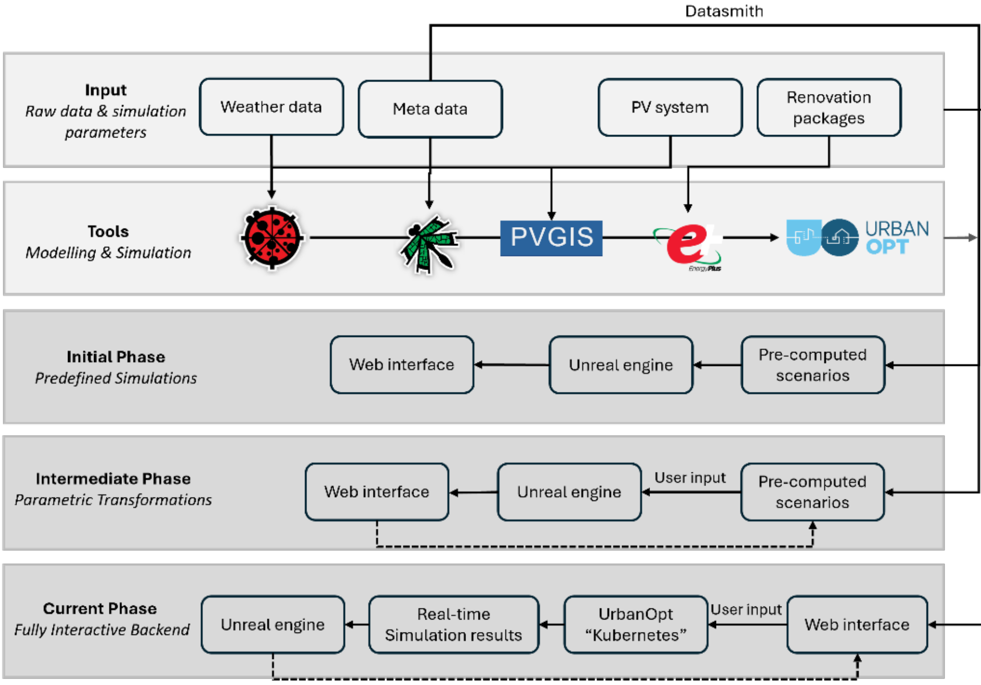

Figure 3. DT4PED System architecture of initial, intermediate and current phases

4.2.2 3D Visualization and Web Deployment

The frontend visualization is built on Unreal Engine, offering a high-fidelity, interactive 3D representation of the district. The geometry is modeled in Rhino, enriched with metadata (e.g., building height and azimuth), and exported via Datasmith into Unreal Engine. Simulation results are linked to building objects using custom parsers, allowing visual overlays and detailed performance feedback. To contextualize the digital twin within its real-world setting, Cesium Ion streams photorealistic terrain and building models into the environment. Time-series simulation data is dynamically accessed, enabling users to query buildings, switch scenarios, and view energy indicators in real time. The complete Unreal

Engine application is deployed online via Pixel Streaming, allowing users to access the twin through a web browser without needing to download or install software. The system consists of:

- A frontend application, developed with Node.js, React/Angular, and TypeScript, bundled into a deployable interface.
- A Signaling Web Server, which manages bidirectional data flow between the browser and the Unreal Engine server instance.

This deployment model ensures broad accessibility while preserving advanced interactive features. The combined architecture supports both expert-driven analysis and inclusive stakeholder engagement, making DT4PED a robust platform for scenario-based PED design and visualization. Unreal Engine 5's rendering capabilities were used to create a detailed 3D model of Jättesten and use Pixel Streaming to deliver this model via a standard web page. The 3D environment is enriched with outputs from the energy simulation: for example, buildings are color-coded by their energy performance, and charts or meters can be presented next to each building showing its solar generation or heating demand. By streaming to a web browser, we ensure that any stakeholder with an internet connection – whether on a laptop, tablet, or smartphone – can access the digital twin viewer without technical barriers. In this study, we leverage URBANopt's capability to simulate multiple buildings with shared energy systems, making it particularly well-suited for modeling Jättesten's diverse building stock and planned energy retrofits. The platform enables scenario-based analyses, providing detailed insights into hourly, monthly, and annual energy demand on the neighborhood scale. Its strength lies in assessing the impact of different renovation packages, particularly in terms of heating demand. Integrated into the same workflow are tools such as Ladybug and PVGIS, which allow for PV potential analysis. By comparing estimated PV production with electricity demand, we evaluate the potential for achieving energy balance or even net-zero performance on a district scale. By using a consistent simulation engine (EnergyPlus) for all scenarios, we ensure that differences in outcomes are attributable to the scenario changes, not modeling inconsistencies. The result is a robust energy simulation backend for the digital twin, providing quantitative outputs (energy use, production, import/export, CO_2 emissions) that feed into the visualization and decision support interface.

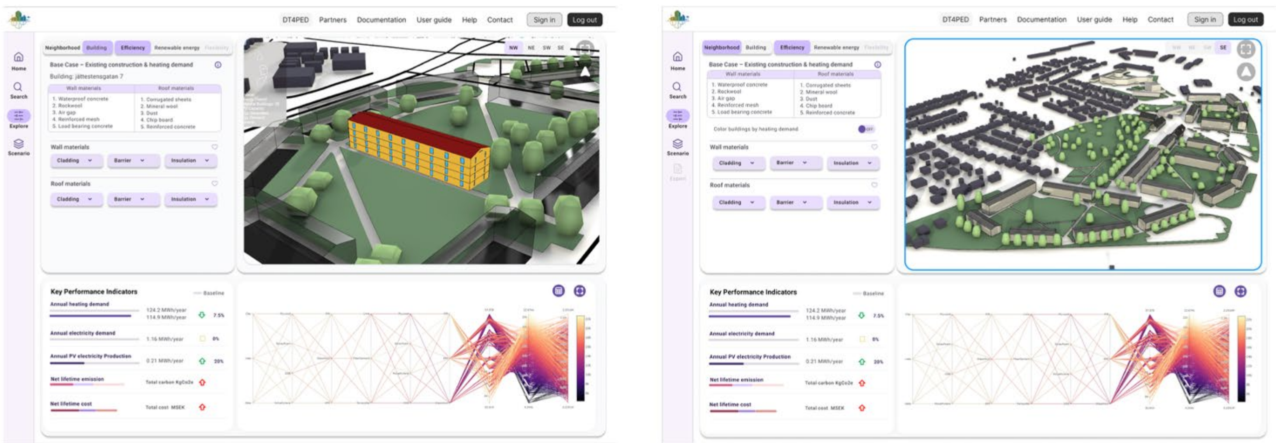

Figure 4. Interactive web-based front end of the simulation platform, showing energy performance visualization for the Jättesten neighborhood on the building and neighbourhood levels.

4.3 UX/UI Test

The results of the UX/UI Test provided valuable input for improving the DT Viewer. The UX/UI test scores provide a quantitative overview of user perceptions across four key areas of the DT Viewer. The highest rated category was *Value & Usefulness*, with an average score of approximately 3.8, indicating that users generally recognized the tool's potential to support decision-making and align with their professional needs. *Content & Information Design* received a moderate score of 3.0, suggesting that while the information presented was considered relevant, there remains room for improvement in clarity and contextual support. *Interaction & Usability* scored lower, 2.8, reflecting challenges with navigation and the need for clearer onboarding and user guidance. The score for *Visual & Interface Design* was reported around 3.0, indicating that the visual quality is comfortable, but still there is a space for improvement. Despite some usability challenges, feedback in the value and usefulness category was overall encouraging. Participants viewed the tool as aligned with their roles and professional needs and acknowledged its potential to support informed decision-making and build user confidence with further development. Overall, the scores highlight the importance of refining interaction flows and improving information presentation, while also affirming the tool's value proposition from the user perspective.

5 Discussion

PEDs represent a one of the important conceprs of the European energy transition, aiming to transform urban areas into net-positive contributors to the energy system through the integration of renewable energy sources, energy efficiency measures, and demand-side flexibility. Unlike isolated net-zero buildings, PEDs operate at the community level, requiring a coordinated interplay of technologies, infrastructures, and user behaviors. This inherently multi-scalar and multi-domain complexity necessitates new forms of planning support and system coordination. DTs have emerged as a key enabler in this context, offering dynamic, data-driven environments for simulating, visualizing, and optimizing PED scenarios. By coupling high-resolution energy modeling with interactive visual interfaces, DTs can facilitate stakeholder engagement, scenario exploration, and evidence-based decision-making. However, the operationalization of DTs for PEDs remains an emerging practice, with limited examples of fully integrated, user-accessible platforms that combine technical rigor with participatory functionality. This study addresses this gap by developing and evaluating a DT framework specifically tailored to the PED planning process. This study contributes to the evolving field of PED planning by presenting a functional, web-based DT platform that integrates detailed energy simulations, advanced 3D visualization, and scenario-based interaction within a single system architecture. The development process was grounded in an interdisciplinary methodology that bridged simulation rigor, spatial visualization, and stakeholder relevance—offering an operational prototype that moves beyond static modeling or conceptual proposals commonly found in the literature.

What sets the DT4PED framework apart is its modular, containerized backend architecture, capable of executing detailed district-scale energy simulations using URBANopt and EnergyPlus in a scalable and reproducible manner. This is coupled with a real-time, browser-accessible interface developed in Unreal Engine, enabling stakeholders to interact with complex simulation results in a visually rich and spatially embedded environment. While elements of this approach draw from existing practices in urban digital twin development, the combination of microservice orchestration, semantic model binding, and live scenario interaction represents a novel integration that extends the state of the art. In particular, the alignment between backend simulation workflows and frontend visualization tools was designed to support iterative use—allowing users not only to view results, but to define and test scenarios dynamically, thus transforming the digital twin into an exploratory decision-support tool.

UESM, especially at the district scale, involves a high degree of technical detail, interdependency, and uncertainty. Capturing these dynamics accurately requires sophisticated models, high-resolution input data, and significant computational infrastructure. However, such complexity can easily become a barrier to practical use—particularly among planning professionals and municipal stakeholders who may not have expertise in energy systems or simulation technologies. One of the core design tensions in this project was therefore the need to balance analytical depth with interpretability: maintaining fidelity in energy modeling while making the results comprehensible and actionable through clear visual and interactive representations. This reflects a broader issue in the digital twin discourse, where delivering technical value must go hand in hand with cognitive accessibility and communicative clarity.

In this context, the UX/UI test served not only as a usability checkpoint but also as a lens through which to reflect on the broader alignment between system functionality and user expectations. While the results identified specific areas for interface improvement, they also confirmed that the platform's core value proposition—namely, supporting scenario-based decision-making for PED development—was understood and appreciated by users. These findings reinforce calls in the literature for digital twins that are not merely technologically advanced but are also meaningful within real-world planning workflows (Kitchin, 2022; Coors, 2023).

Several limitations of the current prototype should be acknowledged. The system is still in an early deployment stage, and certain features—such as time-series comparison tools, modular onboarding sequences, and granular user role differentiation—are under development. Moreover, the computational demands of real-time district simulations remain non-trivial, requiring careful management of performance and scalability in future implementations. Additionally, while the architecture supports dynamic user inputs, the range of parameterization remains constrained by the underlying simulation models and available datasets.

Looking ahead, future work should pursue two parallel trajectories. On the one hand, technical development should focus on improving performance optimization, extending the customization of scenario parameters, and integrating live data streams to move toward a fully cyber-physical twin. On the other hand, more attention should be paid to the institutional embedding of the platform—testing its role within participatory planning settings, policy co-creation processes, and multi-actor governance frameworks. This will require not only technical enhancements but also deeper engagement with questions of legitimacy, data governance, and long-term sustainability of digital planning infrastructures.

This research advances the field by delivering an extensible framework for PED digital twins, capable of integrating complex energy models into an accessible, scenario-driven planning tool. While challenges remain, the DT4PED platform provides a promising foundation for bridging high-fidelity modeling with real-world decision-making, supporting the transition toward more sustainable, resilient, and participatory urban energy systems.

6 Conclusions

This study successfully demonstrates the development and initial evaluation of DT4PED, a proof-of-concept web-based Digital Twin platform tailored for Positive Energy Districts (PEDs). By integrating sophisticated urban energy modeling tools, namely EnergyPlus and UrbanOpt, with a high-fidelity, interactive 3D visualization environment powered by Unreal Engine and disseminated via Pixel Streaming, the platform facilitates dynamic scenario testing and provides a robust basis for informed decision-making in urban energy transitions. The methodology, emphasizing an interdisciplinary approach and stakeholder-centered design, has yielded an operational prototype that transcends static modeling, offering a more engaging and participatory tool for urban planning. While acknowledging the ongoing requirements for performance optimization, expansion of functional features, and more extensive institutional integration, DT4PED represents a promising foundation for bridging the analytical rigor of high-fidelity simulations with the practical demands of real-world urban planning. This work ultimately aims to contribute to the development of more sustainable, resilient, and participatory urban energy systems.

Acknowledgements

This study was developed in collaboration with Digital Twin City Center (DTCC) and our case study partners from housing company Poseidon and Framtiden.

Funding

This project has received funding within the Joint Programming Initiative Urban Europe, financially supported by the Swedish Energy Agency (P2022-01028), the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (894291), and The Scientific and Technological Research Council of Türkiye (122N698). It is also part of the Digital Twin Cities Centresupported by Sweden's Innovation Agency Vinnova Grant No. 2019-00041.

Data Availability Statement

Data is available by request.

Conflicts of Interest

No conflicts of interest

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