An OGC standards-based Urban Digital Twin platform supporting co-creation of Positive Energy Districts: Case study of the Nordbahnhof district in Stuttgart, Germany

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Abstract

Urban Digital Twins (UDTs) are increasingly recognized as enablers of evidence-based planning and citizen engagement. While the involvement of civil society in planning the built environment is well established, its role and motivation in advancing the clean energy transition remain largely unexplored. This paper presents the development and application of an Open Geospatial Consortium (OGC) standards-based UDT platform for the co-creation of Positive Energy Districts (PEDs), as demonstrated through the Nordbahnhof district case study in Stuttgart. The platform integrates interoperable 3D city and energy data using CityGML 2.0 with its Energy ADE 3.0 extension, both compliant with OGC standards to ensure semantic consistency and cross-domain interoperability. SimStadt energy simulation results are stored in the Energy ADE schema within PostgreSQL/3DCityDB database. These data are published through an OGC Web Feature Service (WFS), while 3D city geometries are served as 3D Tiles. In the CesiumJS web-viewer, both services are linked via GML identifiers, enabling coordinated interaction between geometry and energy data for real-time visualization of the district-scale energy balance. The platform was tested with citizens, who learned about load profiles, photovoltaic (PV) potential, and energy efficiency while acting as “district energy planners.” Their responses/willingness to adopt PV and/or modify energy-use behavior were translated into slider inputs to visualize real-time energy-balance outcomes through the platform. Results demonstrate the potential of interoperable, OGC-compliant UDTs to connect data providers, planners, and citizens in a shared decision-support environment. The architecture’s open, modular design enables wider replication, promoting scalability and long-term municipal adoption for participatory energy-transition planning.

1. Introduction

Cities play a central role in addressing climate change, as they account for more than 70% of global energy consumption and carbon emissions. The European Union (EU) has positioned its cities at the forefront of its climate strategy through ambitious initiatives such as the SET Plan Action 3.2, which aims to establish 100 Positive Energy Districts (PEDs) by 2025 and reach 100 climate-neutral cities by 2030. PEDs represent a paradigm shift in urban energy planning, moving from a traditional building-by-building approach towards creating districts that generate more energy than they consume annually. Achieving this goal requires more than technological advancement; it demands an integrated transformation that includes social, political, and behavioral change.

The transition toward energy-positive urban environments relies on both innovation and participation. While the involvement of civil society in shaping the built environment is well established, its active role and motivation in driving the clean energy transition remain limited and underexplored. Recent studies emphasize that citizen participation is not only a moral or democratic requirement but a practical necessity for ensuring the social acceptance and long-term success of energy transition measures. However, involving citizens meaningfully in energy-related discussions continues to face persistent challenges such as a lack of transparency, limited understanding of energy systems, communication barriers between institutions and communities, and insufficient digital tools for co-creation and citizen engagement (Massey et al., 2018). Existing participatory approaches, such as town hall meetings, printed questionnaires, or awareness campaigns, often fail to make energy data and urban transformation scenarios tangible for citizens, leaving them marginalized in decision-making processes. Moreover, the growing complexity of urban energy systems further underlines the need for new, data-driven methods that can connect experts, policymakers, and citizens through shared knowledge environments.

Urban Digital Twins (UDTs), as virtual representations of real-world urban systems, offer a promising framework for bridging technical modeling and participatory engagement. UDTs enable cities to integrate multi-source data, simulate scenarios, and visualize outcomes through interactive interfaces. By connecting computational energy models with geospatial and semantic data, UDTs enable decision-makers to assess the spatial and temporal impacts of interventions, such as the integration of renewable energy, building retrofits, or demand-side management strategies. When coupled with participatory methods such as living labs and co-creation workshops, they create shared visual environments that make complex energy processes understandable, transforming citizens from passive data subjects into active co-designers of the urban energy transition.

The transnational EU research project DigiTwins4PEDs) explores this concept by developing and testing a standards-based UDT platform designed to empower local communities in the

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co-creation of PEDs. The platform leverages Open Geospatial Consortium (OGC) standards, specifically CityGML 2.0 and the newly developed Energy ADE 3.0, to ensure data interoperability, scalability, and integration with existing urban information systems. Built upon a spatially enabled database and linked visualization environment, the UDT allows for the simulation, visualization, and communication of district-scale energy scenarios, including photovoltaic (PV) deployment and behavior change impacts. The framework aligns with the open, interoperable data infrastructures as emphasized in the Digital EU Program.

The Nordbahnhof district in Stuttgart serves as a demonstrator for this prototype, focusing on enhancing citizens’ understanding of energy consumption patterns, PV potential, and the collective benefits of behavioral adaptation. The living-lab process implemented in the Nordbahnhof district uses the UDT platform as an interactive interface to visualize energy scenarios, encouraging citizens to act as “district energy planners.” By allowing citizens to test the impact of their decisions, such as adopting PV systems or shifting their use of electricity-intensive appliances, the platform builds awareness and shared responsibility for local energy transition pathways.

In light of these objectives, this paper introduces the concept, architecture, and implementation of the OGC-compliant UDT platform and its role as a participatory decision-support tool for advancing PEDs. The remainder of the paper is structured as follows: Section 2 reviews the conceptual and technical background of UDTs and PEDs; Section 3 introduces the Nordbahnhof district case study; Section 4 describes the system architecture and data integration workflow; Section 5 presents the development of the UDT platform, Section 6 presents the living lab setup under which the UDT application was tested as citizen engagement tool; Section 7 discusses findings and implications; and Section 8 concludes with reflections and future perspectives. This study aims to demonstrate how an OGC-compliant UDT platform can be developed and applied to support citizen co-creation of PED scenarios, using the Nordbahnhof district in Stuttgart as a case study.

2. Background and Related Work

Understanding how UDTs can support the transition toward PEDs requires a review of the underlying concepts and technologies that shape this field. This section outlines the evolution of UDTs in urban energy planning and discusses the standards and tools that enable their implementation. It highlights how OGC standards, particularly CityGML and the Energy ADE, provide a semantic foundation for linking 3D city models with energy simulations, and how web-based visualization frameworks facilitate their integration into participatory environments. By synthesizing current research, this section identifies the methodological and technological gaps that motivate the development of the UDT platform presented in this study.

2.1 Urban Digital Twins Supporting Energy Transition

UDTs have emerged as a transformative framework for integrating spatial, semantic, and temporal data to support evidence-based decision-making in urban contexts. In the context of energy transition, UDTs act as digital representations of the built environment, capturing both the static characteristics of physical assets and the dynamic behavior of energy systems. This integration enables cities to simulate refurbishment scenarios (Rossknecht and Airaksinen, 2020), evaluate renewable adoption pathways (Rodriguez et al., 2017), and examine the implications of infrastructural change within the same virtual environment.

While numerous UDT applications integrate energy-related indicators such as heating demand, cooling demand, or PV potential, most implementations remain limited to the building scale. Only a limited number of studies have successfully linked these metrics across multiple spatial levels, from individual buildings to entire districts, due to challenges in data harmonization, scale transitions, and semantic consistency (Iossa et al., 2025). Consequently, comprehensive UDT frameworks capable of analyzing energy demand–supply interactions and renewable integration potential across scales are still rare. Recent work highlights that achieving such multi-scalar representations requires standard data models, interoperable simulation workflows, and spatial databases capable of aggregating building-level results into district-level energy balances (Urrutia-Azcona et al., 2025). Establishing these links is crucial for evaluating the PED potential of districts and for supporting energy-transition strategies that reflect the heterogeneity of real urban systems.

Beyond technical modeling, UDTs play a vital role in stakeholder engagement and knowledge transfer. Embedded in participatory settings such as living labs, they serve as collaborative environments that make energy processes understandable to non-experts, fostering inclusiveness and shared ownership in local energy planning (Weil et al., 2023). However, most existing UDT applications remain technologically focused, with limited emphasis on how data interoperability and semantic standards can support replicable, citizen-inclusive workflows for PED planning (Malakhatka et al., 2025). This limitation highlights the importance of adopting standardized, open frameworks that can bridge urban data models, energy simulation tools, and web-based visualization platforms.

2.2 OGC Standards for Semantic 3D City Modeling and Energy Data

A fundamental requirement for operationalizing UDTs is semantic interoperability, which means the ability of heterogeneous datasets and software tools to exchange, interpret, and represent urban information consistently (Rönsdorf et al., 2024). The OGC has long provided the standards framework that underpins this interoperability through open, consensus-driven specifications for geospatial data and services. Among these, CityGML 2.0[1] remains the most widely adopted standard for representing semantic 3D city models, capturing both the geometry and thematic attributes of urban features such as buildings, vegetation, transportation networks, and land-use areas. While the latest version, CityGML 3.0, introduces a restructured data model with enhanced support for time-dependent properties, versioning, and fine-grained spatial concepts, the transition of existing datasets and tools from CityGML 2.0 to 3.0 is still in its early stages of development and is steadily evolving. Therefore, the present study continues to employ CityGML 2.0 as the geometric and semantic foundation, ensuring compatibility with established energy simulation and database environments. The standard’s hierarchical organization allows cities to integrate data at multiple geometric and thematic levels, making it particularly suitable for linking 3D building representations with energy-related information at both building and district-scales.

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[1] `https://www.ogc.org/standards/citygml/`

To extend CityGML toward the energy domain, the Energy ADE[2] (Energy Application Domain Extension) was created as an official OGC extension. Its goal is to provide a standardized data schema that enables both detailed single-building simulations and city-wide bottom-up assessments by embedding data on energy demands, building physics, occupant behavior, and energy systems directly within the 3D city model (Agugiaro et al., 2018). The first version, Energy ADE 1.0, primarily focused on representing operational energy demand and energy system configuration at the building level, supported urban-scale building stock analyses, but without an explicit treatment of renewable energy generation or potential. The subsequent Energy ADE 2.0, a simplified profile developed by the Karlsruhe Institute of Technology, streamlined and reduced model complexity but removed the capacity to store detailed energy system configurations that had been available in version 1.0. Both versions, however, lacked mechanisms for aggregating results or representing multi-sectoral energy data at the district or city level and were unable to represent renewable energy potential, limiting their applicability for assessing district-scale energy balances and PED performance.

The most recent version, Energy ADE 3.0[3], initially released as the new Energy ADE 2.0 but now renamed as Energy ADE 3.0 to avoid confusion (Agugiaro and Padsala, 2025), addresses these limitations and represents a major advancement toward integrated, cross-domain, and multi-scale energy modeling. Building upon developments in the other ADEs (Application Domain Extensions), such as the Food-Water-Energy (FWE) ADE (Padsala et al., 2021) and the Urban Planning ADE (Akahoshi et al., 2020), Energy ADE 3.0 introduces concepts such as Urban Function Areas for district-level aggregation, resource entities for representing cross-domain energy demand-production flows, and enhanced temporal structures for storing annual, hourly, and sub-hourly simulation data. Version 3.0 also reintroduces the representation of energy system configurations, allowing a consistent description of both demand and supply components at building and district-scales. These extensions substantially enhance the ADE’s ability to represent, analyze, and exchange information relevant to PED planning.

In this study, Energy ADE 3.0 serves as the semantic core of the developed UDT framework, ensuring that energy simulation outputs and geometric data share a common reference structure. Energy data generated by SimStadt), including building-level electricity consumption, PV potential, and load profile information, is encoded using Energy ADE 3.0 classes and stored in 3DCityDB/PostgreSQL environment. The integration of CityGML 2.0 and Energy ADE 3.0 establishes a unified, standards-based foundation for representing and analyzing energy-related urban data across multiple spatial scales. Building upon these standards, a modular UDT framework was proposed to operationalize these data models for evaluating district-scale energy balances and renewable energy integration (Padsala et al., 2025). In its initial application, the framework was tested to determine whether the Nordbahnhof district could achieve a net-positive annual energy balance under current conditions, providing a first validation of the workflow. The present study builds on this foundation and applies the same standards-based architecture in a participatory context to enable interactive scenario exploration and citizen engagement for PED planning.

2.3 Web-Based Visualization and Participatory Platforms

Advances in web technologies and information and communication tools have transformed how cities engage citizens in urban planning processes. Open-source technologies, such as CesiumJS, three.js, and commercial technologies, like Mapbox GL JS and the ArcGIS API for JavaScript, have been instrumental in this transformation. Among them, CesiumJS stands out for its performance, open architecture, and native support of the OGC 3D Tiles specification[4], which efficiently streams large-scale 3D city models to web browsers without plugins. Combined with the Web Feature Service (WFS), semantically rich attributes, such as those encoded in Energy ADE 3.0, can be delivered directly to the client, linking 3D geometries with associated energy information in real-time. While the newer OGC APIs for Features, Tiles, and Processes provide lightweight and RESTful alternatives to traditional web services such as WFS (Santhanavanich et al., 2023), their software ecosystem is still evolving. Consequently, this study continues to rely on WFS, which remains the most stable and widely supported standard for interoperable data exchange across current geospatial platforms.

Beyond technical visualization, 3D web platforms increasingly serve as interfaces for participatory planning (Würstle et al., 2021). They enable stakeholders to understand data, test scenarios, and express preferences within interactive environments, transforming citizens from observers into co-creators of urban solutions. Despite growing interest in participatory planning tools, examples that simultaneously integrate quantitative energy simulation outputs, semantic data standards, and real-time 3D visualization within a single interoperable framework remain scarce. Previous participatory tools, such as Smarticipate (Khan et al., 2017) and DIPAS (Lieven, 2017), have demonstrated the value of web-based participation tools; however, these systems do not incorporate energy simulation results or adopt standardized data models for interoperability. Conversely, energy-focused UDT implementations often remain analytically oriented, with limited attention to citizen-facing interfaces or replicable, service-based architectures. The approach presented in this paper attempts to address this gap by combining the newly released Energy ADE 3.0 schema with an OGC-compliant service pipeline and a participatory 3D web visualization environment into a single, openly deployable framework designed to support citizen engagement in PED planning.

3. Case Study Area: Nordbahnhof District, Stuttgart

The Nordbahnhof district (Nordbahnhofviertel), located just north of Stuttgart’s central railway station, serves as the pilot area for developing and testing the participatory UDT platform to support the planning of PEDs. The district is characterized by a dense, mixed-use urban fabric with predominantly residential buildings, complemented by small commercial and social facilities. Its location, directly adjacent to the large Stuttgart 21 redevelopment zone (Rosensteinquartier), places it at the intersection between an established urban district and one of Germany’s most ambitious urban transformation projects. Despite this proximity, the Nordbahnhof district is not included in the official Rosensteinquartier redevelopment plan and therefore risks being socially and infrastructurally disconnected from the new urban extension. These conditions make it an ideal testbed for exploring how UDT technologies can foster participatory

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[2] https://www.citygmlwiki.org/index.php/CityGML_Energy_ADE

[3] https://www.citygmlwiki.org/index.php?title=CityGML_Energy_ADE_V._3.0

[4] https://www.ogc.org/standards/3dtiles/

engagement, shared learning, and data-driven decision-making in support of local energy transition goals.

Beyond its contextual significance, the Nordbahnhof district exemplifies the challenges faced by compact EU districts in transitioning to clean energy, where existing buildings, limited roof space, and diverse ownership patterns hinder the straightforward adoption of renewable energy sources. The district’s CityGML Level of Detail 2 (LoD 2) building data, provided by the Survey Department of the City of Stuttgart, includes detailed roof geometries essential for PV analysis, along with attributes such as building function and year of construction. Together, these datasets form the spatial and semantic foundation of the participatory UDT framework, which is described in the following section.

4. System Architecture and Data Integration Workflow

Building on the standards-based foundation established in previous implementation (Padsala et al., 2025), the present study applies the same OGC-compliant architecture in a participatory context to support interactive scenario exploration and citizen engagement for planning of PEDs. The focus is on demonstrating how an established technical framework can be adapted from an analytical assessment to an interactive, citizen-driven exploration of energy scenarios.

In the previous implementation, the architecture was used to evaluate whether the Nordbahnhof district could achieve a net-positive annual energy balance under current conditions, serving as an initial proof of concept for the integrated UDT workflow. In contrast, the present study applies the same OGC-compliant architecture in the Nordbahnhof district, refining the workflow to concentrate on electricity consumption and PV generation—resources that are directly visible to citizens and closely linked to their everyday energy decisions. Electricity represents the most familiar and immediate form of energy use, while rooftop PV offers a good and practical entry point into the local renewable transition. Focusing on these two aspects provides an intuitive basis for engagement, allowing citizens to easily understand the link between individual behavior, local production, and the district’s overall energy balance. Within this context, the framework was adapted into a participatory decision-support tool rather than a purely analytical model. The implemented architecture (See Appendix Figure 5) follows the same modular design as in the previous implementation, originally developed for district-scale PED evaluation. It consists of three core layers: (1) a **data layer** built on PostgreSQL/3DCityDB, extended with CityGML 2.0 and Energy ADE 3.0 to manage both geometric and semantic energy information; (2) a **service layer** exposing attributes via OGC WFS and geometries via OGC 3D Tiles; and (3) a **client layer** implemented in CesiumJS, where both datasets are connected through shared GML identifiers of CityGML building models for synchronized visualization.

In this study, SimStadt was used to simulate building-level electricity consumption and rooftop PV potential. The resulting datasets were aggregated and stored using the Energy ADE 3.0 schema within the 3DCityDB, enabling subsequent analysis at the district-scale. Visualization and interactive exploration were conducted within the UDT platform, where pre-computed datasets representing varying levels of PV adoption within the district and changes in household energy-use habits, such as shifting the operation of electricity-intensive appliances to periods of high solar power in order to improve local self-consumption from PV systems and therefore reducing dependency on power grid imports were retrieved and displayed dynamically based on user input. This approach directly reflects the PED planning objectives of load shifting and increasing local self-consumption of PV electricity, illustrating how behavioral change and greater renewable penetration in the district can jointly improve the district’s overall energy balance. The MAPED component (Neumann et al., 2021), although part of the overarching framework, was not applied in this study, as the analysis focused on electricity consumption and on-site PV generation from building rooftops, where SimStadt outputs were sufficient to capture the required dynamics.

Overall, the complete architecture functions as a continuous, standards-based data pipeline that links validated 3D city models, semantic energy data, and interactive visualization within a single interoperable environment. This implementation extends the previously analytical framework into an operational, participatory digital twin that enables both energy planners and citizens to explore PED-related scenarios. The following sections describe how this implementation was realized, covering data integration, district-specific datasets, and the logic behind the interactive scenario configuration.

4.1 Data Integration Workflow

The UDT platform for this study is based on the Nordbahnhof district, represented as a CityGML LoD 2 building model obtained from the Survey Department of the City of Stuttgart. The dataset includes key attributes, such as building function and year of construction, which are essential inputs for energy simulation. Before integration with its energy data, building geometries were validated in CityDoctor[5] to ensure their schema validity, geometric correctness, and semantic consistency, with minor inconsistencies resolved by cross-referencing with the publicly available open data[6]. The validated models were imported into SimStadt for energy simulation and subsequently stored in 3DCityDB, where they served as the spatial foundation for integrating energy simulation results and enabling visualization within the UDT platform. The end-to-end workflow, which covers geometry validation, energy simulation, database integration, web service publication (3D Tiles and WFS), and interactive visualization in the UDT viewer, is illustrated in Figure 1.

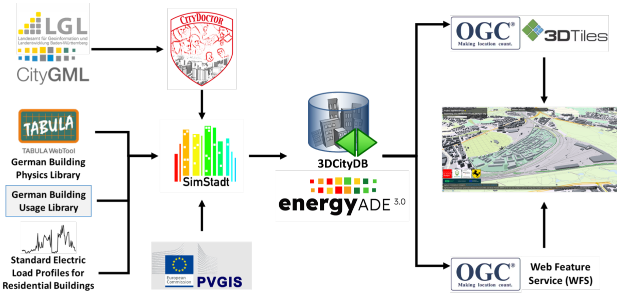

Figure 1. Data workflow and integration pipeline

Energy simulations were conducted in SimStadt, which integrates building physics parameters from the TABULA typology with occupancy schedules and appliance use patterns derived from its German usage library. The standard residential electric

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[5] `https://transfer.hft-stuttgart.de/pages/citydoctor/citydoctorhomepage/en/`

[6] `https://opengeodata.lgl-bw.de/`

load profile was used to represent aggregate household electricity consumption, reflecting typical daily and seasonal variations in consumption. To evaluate the effect of behavioral change, an additional standard load profile was generated by shifting the operation of time-flexible household appliances, such as washing machines, dryers, and dishwashers, to hours with higher PV production, thereby representing a realistic adoption scenario without compromising household comfort. Consequently, each residential building produced two distinct synthetic annual electricity load profiles: a base profile representing typical consumption patterns and a modified profile reflecting shifted appliance use aligned with periods of higher solar generation. Although simulations were also performed for non-residential buildings, the analysis focused on residential ones, where behavioral change is both more feasible and socially relevant. Weather data for the simulations were obtained from the PVGIS database, which is integrated into SimStadt. The resulting outputs included annual electricity consumption, annual load profiles (base and shifted), and annual rooftop PV potential, all computed at an hourly resolution.

In addition to the simulated PV potential, the workflow also accounted for the existing installed PV capacity within the district. Data on operational PV systems were obtained from Germany’s Marktstammdatenregister (MaStR), which reports installed photovoltaic capacities at the postal code level. For postal code 70191, covering the Nordbahnhof area, the reported installed capacity (Bruttoleistung) was scaled to the district boundary using the PV-suitable roof and wall areas derived in SimStadt. This resulted in an estimated installed capacity of approximately 357 kW, corresponding to an annual electricity production of about 365 MWh, roughly 3% of the district’s total electricity consumption from 3% of residential building stock. This value served as the default slider position for PV adoption within the UDT platform, ensuring that the interactive scenarios were initialized with realistic baseline conditions.

To represent the economic dimension of electricity consumption, a dynamic cost profile for 2025 was generated. The baseline of 80 €/MWh reflects the projected average electricity price in Germany for that year, providing a realistic reference for cost estimation under typical market conditions. Hourly price variations were then modeled by applying seasonal and daily multipliers. Distinct weekday and weekend curves captured intraday dynamics, with lower prices during nighttime hours and peaks in the morning and late afternoon, corresponding to typical residential consumption cycles.

All simulation results were encoded according to the Energy ADE 3.0 data model using a custom Python-based importer, which provides dedicated classes to represent energy demand, PV generation, and their temporal dynamics. Building-level electricity consumption, existing PV output, and potential PV yield were stored as Resource objects, while corresponding hourly load profile values (base and shifted) and PV yield production profiles were linked through the Time Series module. The revised temporal structure introduced in Energy ADE 3.0 supports storage of multiple temporal resolutions, allowing detailed building-level analysis as well as aggregated district-scale evaluations within the same schema. For efficient storage and visualization, the original annual hourly profiles (8,760 values per building) were simplified into aggregated 24-hour profiles for summer and winter. An example 24-hour load profile structure for summer in XML encoding of Energy ADE 3.0 is shown below in Listings 1. These simplified profiles not only significantly reduced the data size while still capturing the daily and seasonal variations necessary for interactive scenario analysis in the UDT platform, but also made the results easier for citizens to interpret and relate to during participatory sessions.

Listing 1. Example 24 hours load profile for summer

```
<nrg3:resource>
<nrg3:Energy gml:id="ID_315">
<gml:description>average summer 24 hours
    load profile</gml:description>
...
<nrg3:operationType>demands</
    nrg2:operationType>
...
<nrg3:timeDependentAmount>
<nrg3:TypicalValuesTimeSeries
    gml:id="ID_315_1">
...
<nrg3:temporalExtent unit="day">1.0
    </nrg3:temporalExtent>
<nrg3:timeInterval unit="hour">1.0
    </nrg3:timeInterval>
<nrg3:valuesList uom="kWh">0.132 0.13
    0.136 0.139 0.157 0.28 0.725 0.773
    0.671 0.657 0.672 0.706 0.635 0.658
    0.612 0.564 0.517 0.568 0.809 0.897
    0.814 0.613 0.318 0.166
    </nrg3:valuesList>
</nrg3:TypicalValuesTimeSeries>
</nrg2:timeDependentAmount>
...
<nrg3:endUse>electricalAppliances
    </nrg3:endUse>
<nrg3:energyCarrier>electricity
    </nrg3:energyCarrier>
<nrg3:source>powerGrid</nrg3:source>
</nrg3:Energy>
</nrg3:resource>
```

District-level indicators, such as total electricity consumption, existing PV output, potential rooftop PV yield, base load profile, and energy cost profiles, were aggregated using the Urban Function Area concept of Energy ADE 3.0, which is extended from the CityGML CityObjectGroup class. In this structure, individual buildings are referenced via xlink attributes rather than embedded directly, allowing multiple buildings to be grouped into unified spatial units while preserving semantic traceability and database integrity within 3DCityDB.

All energy-related attributes encoded using the Energy ADE 3.0 schema were published via the OGC WFS. The WFS implementation utilized the Energy ADE 3.0 specific citygml4j and 3DCityDB Java APIs, which manage feature queries, schema mapping, and dynamic filtering of ADE-specific objects. The corresponding CityGML building geometries and the Nordbahnhof district boundary, represented as an UrbanFunctionArea object within the Energy ADE 3.0 data model, were exported as OGC 3D Tiles. Both 3D Tiles and WFS services maintained consistent building gml: ID references, enabling direct one-to-one

Project: DigiTwins4PEDs

Case Study Area: Nordbahnhofviertel, Stuttgart City

Show: Photovoltaic Potential of Residential Buildings

Behaviour Change: 20%

Photovoltaic Coverage: 40%

Time [h]: 10:00
- New load: 1.280,406 kWh
- Current load: 1.045,904 kWh
- PV potential: 1.849,425 kWh

Application developed and managed by Rushikesh Padsala (Rushi) - Click here to contact me

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Figure 2. UDT platform supporting co-creation of PEDs with Citizens

linkage between geometric entities and their associated energy attributes within the client application.

To enhance contextual visualization, a high-resolution digital elevation model of the terrain provided as an open data service by the Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany (AdV)[7] was integrated as a web service. The official German topographic basemap, accessible openly via Web Map Service (WMS)[8], was also added to provide contextual cartographic references. In addition, surrounding buildings published by the AdV as 3DTiles in LoD 2 were also included to maintain visual continuity beyond the Nordbahnhof boundary. Together, this integrated data and service environment formed the basis of the participatory UDT platform, enabling the co-creation of PEDs with citizens.

5. Development of the UDT Platform and Its Elements

Building on the system architecture and data integration workflow described in section 4, the interactive UDT platform (Figure 2), transforms the prepared datasets into an intuitive engagement environment for both planners and citizens. Instead of running new simulations on the client side, the platform dynamically retrieves pre-computed results stored in the Energy ADE 3.0 schema within the 3DCityDB through stored queries delivered via WFS, ensuring smooth and responsive interaction within the CesiumJS viewer.

As illustrated in Figure 2, two scenario sliders form the interactive core of the UDT platform. The behavior change slider is connected to a WFS endpoint that retrieves residential buildings ranked by their total annual electricity consumption, starting from the highest values. The PV-adoption slider, on the other hand, connects to another endpoint that delivers residential buildings ordered by their rooftop PV potential, from highest to lowest. Both endpoints use stored queries configured within the OGC WFS service, allowing the client to flexibly request data according to user-defined slider positions.

When users adjust the sliders, the client dynamically retrieves the corresponding pre-computed simulation datasets from the Energy ADE stored in 3DCityDB. Increasing the PV-adoption slider activates buildings in order of their rooftop potential, allowing users to explore how a gradual increase in PV coverage affects the district’s energy balance. Adjusting the behavior change slider alters the proportion of households using shifted-load profiles in which certain appliances, such as washing machines, dryers, or dishwashers, are assumed to operate during midday hours that coincide with higher solar availability. The combined effect of these adjustments is processed directly within the client, which aggregates updated load profiles for the entire district. For each slider adjustment, the platform automatically updates key performance indicators (KPIs) that are calculated directly in the client. The main KPIs displayed include: (1) **PV coverage (%)** – the percentage of total electricity consumption met by local PV generation; (2) **grid share (%)** – the remaining portion of electricity consumption supplied by the external power grid; and (3) **annual cost savings (%)** – the percentage reduction in annual electricity expenses of the district.

PV coverage and grid share are calculated by comparing the hourly PV generation curve with the corresponding building-level electricity consumption. For each timestamp, PV production is first used to meet the building’s own electricity demand. The portion of demand directly covered by PV represents PV coverage. If PV generation exceeds consumption at that moment, the surplus is considered exported to the grid (or stored) and is not counted toward coverage. The remaining unmet demand is covered by the power grid and therefore contributes to the grid share KPI. The cost-saving KPI is derived by applying the hourly cost profile to both the base and modified load conditions. The difference in total annual cost between these two cases is then expressed as a percentage, showing the potential financial benefit of increased PV adoption or load shifting for the district.

Through this setup, the sliders act as intuitive controls that translate user interaction into measurable outcomes, allowing both citizens and planners to explore how different choices influence district-scale energy dynamics. As users adjust the sliders, corresponding load profile charts are dynamically updated to

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[7] `https://basemap.de/produkte-und-dienste/3d/`
[8] `https://basemap.de/produkte-und-dienste/web-raster/`

visualize the relationship between household electricity demand and PV generation, providing immediate feedback on how local actions affect the overall energy balance. Calculations are based on representative 24-hour summer and winter profiles, which preserve daily and seasonal variability while minimizing data load on the client. This design keeps the UDT platform lightweight and responsive, making it well-suited for citizen engagement and the co-creation of PED scenarios, where citizen inputs directly shape the simulated energy outcomes.

6. Urban Living Lab Implementation

To evaluate the participatory potential of the UDT platform, different urban interventions were carried out as living labs in the Nordbahnhof district. The living lab served as a space where citizens, planners, and researchers jointly explored how everyday decisions could influence the district's transition toward a PED. The sessions were designed to build understanding, gradually moving from simple demonstrations of energy concepts to hands-on interaction with the UDT platform.

The workshops were structured in three stages. The first stage introduced citizens to the idea of energy demand and daily load variations through an interactive "load profile demonstrator" (physical board game). This exercise enabled citizens to visualize how household electricity consumption fluctuates over 24 hours and how adjusting the use of certain appliances could alter the overall profile.

The second stage used a collaborative LEGO-based card game to stimulate discussion about how load profiles are constructed (Figure 3). In this activity, colored LEGO bricks represented hourly electricity use over a 24-hour period. Citizens built their own household load curves by stacking bricks corresponding to appliance use throughout the day, such as cooking, washing, or entertainment.

Figure 3. LEGO-based card game for constructing load profiles

The third stage brought these ideas into the digital world through the UDT platform, deployed on a large touch-table interface (Figure 4). Groups of five to ten citizens were invited to act as "district energy planners" and experiment with two adjustable sliders representing PV adoption and behavioral change scenarios. Each session lasted approximately 20 minutes and began with a brief introduction that explained the purpose of the developed UDT platform and how the sliders functioned. The moderator guided citizens through the interpretation of graphs and KPIs, encouraging reflections on achievable actions. Through an online audience participation tool (Mentimeter), citizens were asked two guiding questions: (1) to what extent should households adjust appliance use to better match solar availability, and (2) how much of the district's rooftop PV potential should be used. Citizens' responses were entered into the UDT platform's two scenario sliders, which instantly updated the charts and KPIs, allowing citizens to better understand the interdependencies between electricity consumption, PV generation, and costs.

Figure 4. UDT platform deployed on touch-table (right) and partial view of the load profile demonstrator (left)

Overall, the living lab sessions demonstrated that citizens can engage meaningfully with complex energy information when supported by interactive digital tools, such as the UDT platform. This underscores the platform's potential to serve as both an educational resource for citizens and a participatory decision-support system, promoting a shared understanding and more collaborative approaches to energy transition at the district-scale.

7. Discussion

The living lab activities demonstrated that digital twin technologies, paired with simple and relatable tools, can effectively bridge the gap between abstract energy modeling and citizens' practical understanding. The stepwise approach from exploring load profiles via the demonstrator, to building LEGO-based profiles, to interacting with the UDT platform helped citizens grasp how household energy behavior and rooftop PV penetration influence district-level performance, transforming technical outputs into accessible knowledge, and allowing citizens to observe in real-time how collective choices affect district-level KPIs.

That said, the robustness of the engagement process is supported by a hybrid, low-threshold, and intergenerational design that promoted inclusivity, active participation, and experiential learning, with impact assessed through energy behavior questionnaires and qualitative insights gathered during sessions. Adaptability is central to the co-creation approach, enabling continuous feedback and iterative adjustments throughout the process. Transparency is supported by adherence to FAIR principles, open communication channels, and the active involvement of the City of Stuttgart, ensuring accountability and institutional trust. It should be noted, however, that the sessions involved a limited number of participants within a single district, and the outcomes reflect immediate reactions during facilitated workshops rather than formally validated behavioral intentions. To support replication, documentation, and open access to methodologies, data, and tools are provided, with the process being tested in three additional European cities, contributing to cross-context transferability.

The UDT interface (Figure 2) presented energy data through an interactive 3D view supported by simple charts and indicators. Buildings were color-coded by their annual PV potential, while three charts displayed the updated district performance: a coin-style animation summarizing cost savings, a bar chart comparing PV coverage and grid share, and a 24-hour line chart contrasting base and modified load profiles overlaid by a PV potential curve for representative summer and winter days. This immediate visual feedback made it easy for citizens to interpret the relationship between electricity demand, on-site generation, and economic outcomes, helping them see how even small shifts in behavior or PV adoption can improve district-scale energy balance.

An important goal of the exercise was to promote a shift in perception, from viewing citizens purely as consumers of electricity to recognizing them as potential prosumers. In the energy-transition context, prosumers are individuals or households who not only consume energy but also produce it, typically through rooftop PV systems, while actively managing their consumption patterns. The UDT platform provided a tangible environment to experience this role change. By adjusting the sliders, citizens effectively decided how much electricity the district would generate and how flexibly they would use it, turning a complex energy planning concept into a hands-on learning experience. Through the combination of teaching tools and the UDT platform, citizens quickly understood that achieving a PED is not only a technical challenge but also a behavioral one. Real-time updates of the KPIs helped them connect individual actions with collective outcomes, reinforcing the idea that broad adoption of renewable energy and coordinated changes in energy-use habits can significantly reduce grid dependency and energy costs. It is also important to note that focusing exclusively on electricity consumption and rooftop PV generation provides only a partial view of the broader energy balance required for a comprehensive PED assessment. This narrowing of scope was intentional, as electricity and rooftop PV are the dimensions most directly connected to citizens’ everyday experience. Future extensions of the UDT platform are planned to incorporate heating, cooling, and mobility-related energy demand, enabling a more complete evaluation of district-level PED performance.

From a technical perspective, the experiments validated the robustness of the standards-based architecture. Pre-simulated datasets combined with OGC-compliant web services delivered near-instant responses without compromising semantic richness. Using simplified 24-hour summer and winter profiles ensured responsiveness while preserving seasonal realism, an essential balance for participatory applications where simplicity and reaction time are more critical than full-year simulation precision. The current implementation relies on a CityGML LoD 2 building model with roof geometry, and publicly available datasets such as PVGIS and the national PV registry. While these inputs are increasingly accessible across European cities engaged in 3D city modeling initiatives, cities with limited GIS infrastructure or less detailed building stock data may face additional barriers to full replication. The modular, service-based architecture of the platform is designed to accommodate partial implementations, for example, using simplified LoD 1 building geometries or alternative simulation tools, though the depth and precision of the resulting simulation results may vary accordingly. Regarding the accuracy of energy simulation results from SimStadt, it should be noted that the simulations rely on building archetypes from the TABULA typology and standard load profiles, rather than measured consumption data or smart meter readings. As a result, the outputs carry inherent uncertainties related to occupant behavior variability, building condition heterogeneity, and local microclimate effects not fully captured by the weather data inputs. The simulated results are therefore best interpreted in relative terms, as indicators of the potential impact of different PV penetration rates and load-shifting adoption rate, rather than as precise energy forecasts for individual buildings or the district.

For practitioners considering replication of this approach, the core technical requirements include a CityGML LoD 2 building model with roof geometry sufficient for PV analysis, a building energy simulation tool that either natively supports the Energy ADE 3.0 schema or whose outputs can be mapped to the Energy ADE 3.0 schema using external tools such as FME (an example workbench is available here) or custom Python importers such as the one developed in this study, a 3DCityDB/PostgreSQL instance along with its importer-exporter GUI for hosting the Energy ADE 3.0 package [9], and a web server capable of hosting OGC WFS (e.g. Apache Tomcat) and 3D Tiles services (e.g. Apache HTTP Server). All principal software components used in this study are open-source or freeware.

Overall, the results indicate that a UDT, when designed around open data standards and participatory principles, can serve as both an analytical tool and a medium for civic engagement and dialogue. By making energy data transparent and interactive, the platform encourages citizens to understand, question, and eventually co-create energy-positive futures for their districts, thus transforming them from passive observers into active stakeholders in the transition toward PEDs.

8. Conclusion and Future Work

This study demonstrated how a standards-based UDT architecture can be adapted into a participatory platform that connects citizens and planners in co-creating PED scenarios. By combining pre-simulated datasets, intuitive visualization, and interactive controls, the platform successfully translated complex urban energy dynamics into an accessible, real-time learning experience. The living lab workshops showed that such tools can foster greater awareness, engagement, and a sense of shared responsibility in the local energy transition. Looking ahead, additional interactive parameters, such as battery electric vehicle adoption and its impact on district energy balance, building refurbishment measures, replacing energy-intensive devices/appliances with energy-efficient ones, and adoption of heat pumps, are under development. These extended scenarios will allow participants to explore broader aspects of decarbonization and clean energy transitions. Additional KPIs, including the self-sufficiency ratio, energy storage potential, and carbon emission reduction potential, are also being integrated to provide a more comprehensive understanding of PED performance.

From a technical perspective, the same standards-based architecture is currently being tested in other case studies across Europe, including Vienna, Rotterdam, and Wroclaw. Insights from these implementations will contribute to the development of best-practice guidelines for creating interoperable, citizen-inclusive UDT platforms, particularly in the context of sustainable energy planning and management. A key design choice in the implementation was the adoption of a service-based architecture. This approach mirrors real-world institutional structures,

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[9] `https://github.com/tudelft3d/Energy_ADE`

in which different municipal departments are responsible for different data domains. For example, surveying offices maintain 3D city models, while environmental or energy departments manage energy-related datasets. By linking these distributed datasets through standardized web services (e.g., OGC WFS and 3D Tiles), the UDT framework supports decentralized data management while enabling seamless integration within a single interactive environment. This architecture thus reflects both the technical and organizational realities of urban data governance. The long-term goal is to establish a methodological and technical framework that supports not only professional energy planners and decision-makers but also citizens, transforming them from passive consumers into prosumers and active co-creators of PEDs.

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Appendix

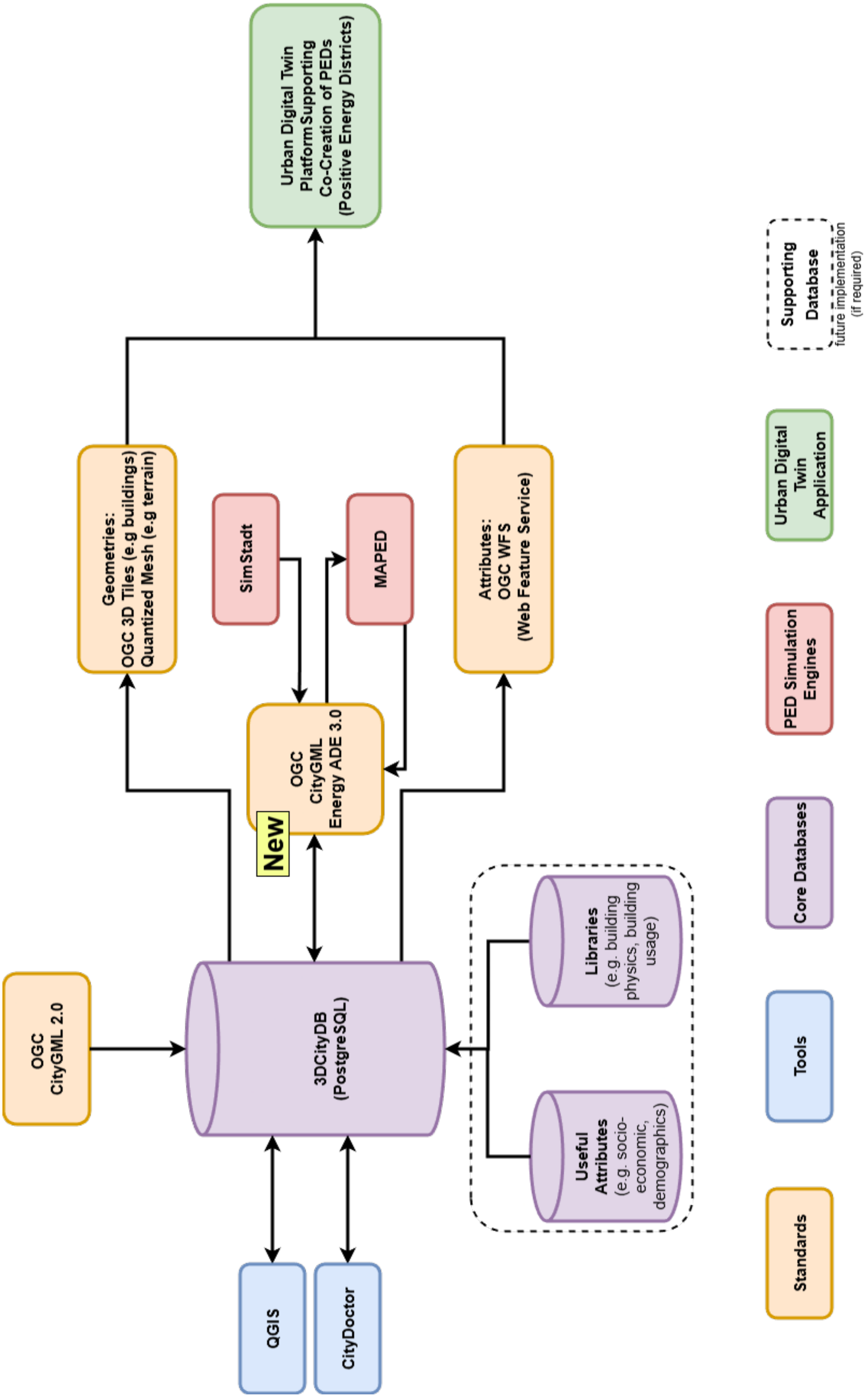

Figure 5. An OGC standards-based UDT framework