# A Data-Driven Urban Digital Twin Approach for Evaluating Positive Energy District Potential Using OGC Standards in Stuttgart

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**Abstract**

This article introduces an urban digital twin workflow based on OGC standards and newly developed Energy ADE 2.0 that integrates building-scale simulations from SimStadt with district-level assessments using MAPED, connected through interactive web-based visualisation. This approach delivers a modular, open-source pipeline that harmonises multi-scale energy data and enables data-driven scenario analysis and stakeholder engagement in support of net-positive energy planning for urban districts. By connecting detailed simulation tools with standardised, spatially linked data models, the study advances the methodological foundation for assessing Positive Energy Districts (PED) using digital technologies and provides a practical decision-support system for planners and policy-makers involved in sustainable urban transformation.

## 1. Introduction

As global urban populations continue to grow, cities face unprecedented challenges in achieving climate neutrality and sustainable development. The European Union's ambition to achieve carbon neutrality by 2050 has positioned urban areas as critical battlegrounds for reducing greenhouse gas emissions and transitioning to renewable energy systems (European Commission, 2020). Within this context, the concept of Positive Energy Districts (PEDs) — urban areas that generate more energy than they consume annually through renewable sources and energy efficiency measures — has emerged as a transformative strategy for sustainable urban planning (Derkenbaeva et al., 2022). PEDs represent a paradigm shift, moving beyond traditional energy efficiency to create urban ecosystems that actively contribute to energy surplus, thereby supporting broader climate goals. However, assessing the PED potential of existing urban districts is a complex endeavour, requiring integrated analyses of building-level energy performance, district-scale energy flows, and the interplay of socio-technical factors such as building typologies, renewable energy integration, and stakeholder priorities.

The advent of urban digital twins — virtual replicas of physical urban environments enriched with real-time and/or simulated data — offers a promising framework for addressing these challenges. Urban digital twins enable multi-scalar analysis, scenario exploration, and stakeholder engagement by integrating diverse datasets, simulation tools, and visualisation platforms (Zhang et al., 2021). Despite their potential, many existing urban digital twin frameworks lack standardised data models and interoperable architectures, which hinders their ability to harmonise energy-related data across spatial and temporal scales. This fragmentation limits effective communication between simulation tools, planning systems, and stakeholders, including policymakers, urban planners, and residents. To overcome these barriers, there is a pressing need for modular, open-source, and standards-based approaches that can seamlessly connect high-resolution energy simulations with district-level assessments within a unified digital environment.

This paper introduces a novel urban digital twin workflow designed to evaluate PED potential in urban districts, with a focus on the Nordbahnhofviertel district in Stuttgart, Germany. Grounded in Open Geospatial Consortium (OGC) standards, including CityGML and the newly developed Energy ADE 2.0 (Energy Application Domain Extension) [1], the proposed approach integrates building-scale energy simulations from SimStadt with district-level energy planning using the MAPED tool. These components are connected through a web-based visualisation platform built on OGC-compliant 3D Tiles and Web Feature Services (WFS), enabling interactive exploration of energy metrics and scenario outcomes. By leveraging open-source tools and standardised data models, the workflow ensures transparency, scalability, and adaptability across diverse urban contexts.

The present study is conducted within the framework of the EU-funded DigiTwins4PEDs project[2], which seeks to co-create Positive Energy Districts (PEDs) in collaboration with citizens. From a technical standpoint, the project advances data-driven urban energy planning by leveraging urban digital twins within a living lab environment. This approach is designed to support citizen-led transitions toward clean energy adoption and is implemented across four diverse case study districts within the European Union. One of these is the Nordbahnhofviertel

[1] not to be confused with the KIT profile of Energy ADE 1.0, which is openly available and distributed as Energy ADE 2.0.
[2] `https://digitwins4peds.eu/`

district — a mixed-use area adjacent to Stuttgart's transformative "Stuttgart 21" redevelopment, which serves as a compelling case study due to its isolation from major infrastructure investments and its heterogeneous building stock. By applying the proposed pipeline, this research evaluates Nordbahnhofviertel's potential to achieve a net-positive energy balance and identifies scenario-based pathways to enhance its PED potential. Beyond the Stuttgart case, the workflow's adaptability is demonstrated through its application in other European districts, underscoring its broader relevance for sustainable urban transformation.

This paper contributes to the growing field of urban digital twins by presenting a practical, standards-based framework for PED assessment. It addresses key methodological gaps in multi-scalar energy modelling and stakeholder engagement, offering a replicable decision-support system for planners and policymakers. The remainder of the paper is structured as follows: Section 2 reviews the state-of-the-art in urban digital twins and PED assessment; Section 3 details different components of the system architecture; Section 4 presents the Nordbahnhofviertel case study with its preliminary results in Section 5 and Section 6 concludes by summarising progress and outlining next steps in ongoing work.

## 2. State of Art

Research in urban energy planning has increasingly leveraged digital technologies to address the complex demands of sustainable development, with PEDs emerging as a key focus. Urban digital twins, semantic 3D city models, and advanced simulation platforms have become central to these efforts, supported by standardised frameworks like those from the Open Geospatial Consortium (OGC). This literature review examines the current landscape of urban digital twins, OGC standards, energy simulation tools, and web-based visualisation platforms in the context of PED assessment, identifying gaps that this study seeks to address.

Urban digital twins serve as virtual platforms that integrate spatial and non-spatial data to model urban infrastructure and dynamic processes, such as energy flows (Batty, 2024). They enable multi-scalar analysis, scenario testing, and stakeholder engagement, making them well-suited for PED planning (Weil et al., 2023). However, inconsistent data standards often hinder interoperability, limiting their scalability across diverse urban contexts (Lei et al., 2023). OGC's CityGML standard addresses this by providing semantic 3D city models that capture geometric and attribute data for urban objects, with Level of Detail 2 (LoD2) models supporting energy simulations through detailed building representations (Padsala et al., 2020). The Energy Application Domain Extension (ADE) further enhances CityGML by adding energy-specific attributes, such as demand profiles and renewable potential (Agugiaro et al., 2018). While Energy ADE 1.0 has supported large-scale building stock analyses in urban contexts — such as in London and Helsinki (Rosser et al., 2019, Rossknecht and Airaksinen, 2020) — it lacks the structural capability to represent cross-sectoral interactions (e.g., between energy, water, and food systems) and to model energy-related metrics across multiple spatial scales. This is particularly limiting for evaluating annual energy balances and understanding energy flows at the district level, which is essential for PED assessments. These constraints prompted the development of Energy ADE 2.0, which builds upon conceptual foundations introduced in the Food-Water-Energy (FWE) ADE — developed to capture interdependencies within the FWE nexus (Padsala et al., 2021) — and the i-UR Urban Planning ADE covering detailed attributes of city objects and mechanisms for global representation and analysis necessary for urban planning.(Akahoshi et al., 2020). Among its key innovations, Energy ADE 2.0 - refer section 3.2.2 introduces the concept of Urban Function Areas to enable spatial aggregation at the district scale, and the Resource class to explicitly represent and link cross-sectoral urban energy-related datasets (Agugiaro and Padsala, 2025). These enhancements significantly expand the ADE's capacity to support integrated, multi-scale, and cross-domain analysis for data-driven urban energy planning.

To effectively operationalise the data structures and semantic models enabled by Energy ADE and CityGML, robust urban energy simulation tools are essential for PED planning and assessment. Most existing simulation tools operate at a single spatial scale—either at the building level (e.g., SimStadt - refer section 3.3.1, EnergyPlus, CitySimPro, TEASER) or at the aggregated district level (e.g., MAPED - refer section 3.3.2) . Building-scale tools like SimStadt generate detailed energy performance metrics for individual buildings, which are critical for assessing a district's PED potential. However, a comprehensive evaluation of a district's annual energy balance can only be achieved at the district scale. Therefore, effective PED planning requires integrating building-level and district-scale simulation tools. In this integrated approach, building-scale tools supply granular energy data that can be aggregated and analysed by district-scale tools. This exchange of data is facilitated through standardised semantic models such as Energy ADE. District-scale tools like MAPED often rely on assumptions about building performance, but integration with detailed building-level simulations enables them to use data-driven inputs, enhancing accuracy and reducing reliance on generalisations. Our prior work proposed the integration of SimStadt and MAPED for multi-scalar PED scenarios — an approach that this study advances using Energy ADE 2.0 (Coors and Padsala, 2024).

Web-based visualisation platforms are crucial for making simulation outputs accessible to stakeholders. Tools like CesiumJS and ArcGIS API enable interactive 3D visualisation of CityGML models via OGC 3D Tiles and i3s (Coors et al., 2018). Although newer OGC APIs (e.g., Features, Tiles, Processes) offer lightweight, RESTful alternatives to legacy standards like WFS and WPS (Santhanavanich et al., 2023, **?**), limited software support means this study continues to use WFS to deliver Energy ADE 2.0 data. Participatory platforms, such as the 3D city model system used in Stuttgart's Weilimdorf redevelopment, show strong potential for citizen engagement in PED planning—an aspect emphasised in our previous work (Würstle et al., 2021, Reber et al., 2025). However, linking energy simulations to participatory platforms remains an active challenge (McGookin et al., 2021).

Despite progress, key gaps remain. Standardised frameworks for multi-scalar energy analysis are limited, impeding tool interoperability. Integration of diverse simulation tools (e.g., SimStadt, MAPED) within OGC-compliant digital twins is underexplored, particularly for PEDs. Participatory platforms for PED planning are also nascent, lacking robust connections to simulation outputs. This study addresses these gaps with an OGC-compliant urban digital twin workflow integrating SimStadt, MAPED, and Energy ADE 2.0, coupled with a CesiumJS-based platform for interactive PED assessment in Stuttgart's Nordbahnhofviertel.

## 3. System Architecture

This section presents the system architecture designed to assess the energy balance of urban districts. It is based on a modular, standards-compliant framework that leverages open-source tools/freeware to construct an urban digital twin for evaluating net-positive energy potential (Figure 1 - See Appendix). The following subsections describe the core components of the workflow and their respective functions within the system.

### 3.1 3D City Models

3D city models form the spatial backbone of urban digital twins, offering a semantically rich, geometrically accurate representation of the built environment. These models enable the integration of diverse urban data—ranging from building morphology and land use to energy attributes—within a common spatial framework. In the context of energy simulation, 3D city models provide the necessary geometric and semantic detail for calculating building energy demand, evaluating solar potential, and assessing retrofit scenarios at scale. Their structured format, especially when based on standards like CityGML, ensures interoperability with simulation engines and urban platforms, thereby playing a critical role in enabling scenario-based analysis and informed decision-making for sustainable urban development.

**3.1.1 OGC CityGML** is an open data model and XML-based format for the representation of 3D city models. It provides a standardised way to encode the geometry, topology, semantics, and appearance of urban objects, enabling consistent data exchange and integration across various applications. The most recent version, CityGML 3.0, introduces enhanced capabilities for time-dependent representations, modular ADE support, and refined semantics (Kutzner et al., 2020). However, due to limited software support and tooling maturity, CityGML 2.0 remains the de facto standard in many workflows, including the present study.

CityGML's structured semantic richness makes it particularly valuable for energy simulation, where both geometric detail (e.g., LoD2) and attribute data are essential. Among the available attributes, building function and year of construction are especially critical, as they determine occupancy patterns and construction typologies—key parameters in most energy demand models. These attributes are typically obtained from municipal city survey departments or cadastral databases and can be integrated into CityGML-based workflows to support district-scale energy assessments and scenario planning within urban digital twin environments.

### 3.2 Data Management Tools

**3.2.1 3DCityDB** (version 4.4.2 in this study) is an open-source spatial database system designed to store, manage, and exchange 3D city models based on the CityGML standard. It provides a robust framework for organising semantic, geometric, and topological data of urban environments, supporting applications in sustainable urban planning, including Positive Energy District (PED) assessment. Compatible with PostgreSQL/PostGIS, Oracle Spatial, and PolarDB/Ganos, 3DCityDB efficiently handles multi-scale, semantically rich city models and supports data exchange in formats such as CityGML, CityJSON, KML, COLLADA, and glTF. Its Importer/Exporter Tool (version 5.5.1 in this study) streamlines the import, export, transformation, and visualisation of CityGML datasets, ensuring interoperability across platforms. 3DCityDB suite (version 2024.0.2 in this study) [3] contains all components bundled for seamless integration and operation within urban digital twin workflows.

**3.2.2 CityGML Energy ADE 2.0** To provide a standardised structure for urban energy data, the Energy ADE was released in 2018 as an official extension of CityGML 2.0 (Agugiaro et al., 2018). It has since enabled both building-level simulation and city-wide energy assessments in multiple European projects. Based on CityGML's Core and Building modules, Energy ADE 1.0 introduced six thematic modules covering building physics, systems, occupants, materials, and time series. However, its scope was limited to energy demand and lacked support for multi-resource modelling and spatial aggregation.

Building on these experiences, Energy ADE 2.0 has been under active development since 2024. While still aligned with CityGML 2.0 for compatibility, its structure has been revised to facilitate future integration with CityGML 3.0. Key enhancements include a more modular design, harmonization with other ADEs, and the introduction of two important additions: the Resources module, which enables the representation of multi-sectoral resource flows (e.g. energy, water, waste) including actual and potential values; and the Urban Function Area module, which allows aggregated data to be linked to spatial units like blocks or districts. These additions significantly strengthen the model's ability to support cross-sectoral urban-scale energy analysis and scenario-based planning at different spatial scales.

The Resources module generalises the previous concept of energy demand by allowing any city object to consume, produce, or store various resources, including energy, water, food, waste, and construction materials. It supports both absolute and normalised values, time series data, and optional indicators such as carbon equivalents and economic costs. Inspired by the Food-Water-Energy ADE, this module enables more holistic modelling of urban resource flows and supports circularity assessments by treating buildings and infrastructures as dynamic resource nodes.

The Urban Function Area module complements this by enabling the grouping of city objects—such as buildings—into meaningful spatial units like blocks, neighbourhoods, or districts. These groupings, derived from the CityGML CityObjectGroup class and extended from the i-UR ADE, allow for the assignment of aggregated energy or resource data to defined areas. The module supports both administrative boundaries and custom geometries, allowing for flexible integration with statistical zones, planning areas, or user-defined units.

To support the practical implementation of Energy ADE 2.0, two Java-based libraries are currently in development. One extends the citygml4j API to support reading and writing CityGML with Energy ADE 2.0 content. The other ensures import and export functionality within the 3DCityDB Importer-Exporter tool. As an interim solution, a dedicated FME workbench enables importing Energy ADE 2.0 data into a 3DCityDB schema extended via DDL scripts. All tools and code repositories are maintained through the official Energy ADE 2.0 GitHub repository[4].

[3] https://github.com/3dcitydb/3dcitydb-suite
[4] `https://github.com/tudelft3d/Energy_ADE_2.0`

**3.2.3 Supporting Databases** To enrich the semantic content of the 3D city models stored in the 3DCityDB, additional supporting databases may be integrated when required. These include domain-specific libraries (e.g., for building physics or usage profiles - if not part of the energy simulation software) and external attribute sources (e.g., socio-economic or demographic datasets). While not mandatory for initial implementation, these resources offer valuable contextual data for enhancing energy simulations and refining PED analyses. Their inclusion facilitates a more holistic urban digital twin by enabling detailed parameterisation and scenario modelling at scale.

### 3.3 Energy Simulation Tools

**3.3.1 SimStadt** is an urban energy simulation platform[5] developed since 2014 at the Stuttgart University of Applied Sciences (HFT Stuttgart), models building-level energy demand and supply with high temporal resolution (Nouvel et al., 2015). It leverages CityGML-based 3D city models to simulate heating and cooling demands, electricity load profiles, photovoltaic (PV) potential, and carbon emissions, therefore producing high-resolution building energy data required for PED planning and assessments. SimStadt's modular workflow includes processors for building preprocessing, physics, usage, weather, irradiance, and monthly energy balance. The preprocessing module imports and validates CityGML datasets, generating SimStadt-specific models. The physics module assigns attributes (e.g., U-value, infiltration rate) based on construction year, using archetypes from IWU German typologies and DIN V 18599. The usage module defines occupancy, internal gains, and hot water consumption by building function. If attributes like building function or construction year are missing, defaults (e.g., residential, 1980) are applied. SimStadt's flexibility allows adaptation to local archetypes and boundary conditions, as demonstrated in different research studies [6].

**3.3.2 MAPED** The Model for Analysis of Positive Energy Districts (MAPED) is a bottom-up, rapid assessment tool developed to evaluate the energy performance of urban districts and their potential to achieve an annual positive energy balance. Based on the end-use concept of the IAEA's MAED model (Neumann et al., 2021) and developed by the Austrian Institute of Technology (AIT), MAPED estimates useful and final energy demand across sectors—residential, service, industry, urban farming, and mobility—and compares it with local renewable supply potential. It evaluates how technologies like PV, solar thermal, and heat pumps can meet heating and electricity needs, while factoring in options like biomass or waste heat. MAPED helps identify PED strategies such as building retrofits, efficiency improvements, electrification, and on-site renewables. It also supports assessing demand flexibility and storage to enable grid and district heating interaction.

MAPED's core approach is scenario-based and relies on demographic, socio-economic, and technological data to model energy demand evolution over time. It links energy service needs—such as space heating, domestic hot water, lighting, and appliances—to key drivers including population dynamics, household size, dwelling characteristics, equipment efficiency, and technology adoption rates. These variables are introduced as exogenous scenario inputs, enabling users to explore plausible transition pathways under varying policy or development conditions. This fine-grained modelling ensures that district energy simulations are grounded in realistic usage patterns and evolving social and technological trends. A key feature of MAPED is its ability to aggregate building-level energy simulation results—such as thermal loads and PV potential—using the Energy ADE 2.0 data structure. These values are spatially linked to Urban Function Areas, allowing for district-wide evaluation of net annual energy balance (on-site generation minus demand), sector-specific carbon emissions, and the contribution of local renewables. The focus remains on stationary end-uses, excluding more variable and less controllable sectors like freight transport, to retain local decision-making relevance.

[5] https://simstadt.hft-stuttgart.de/
[6] https://simstadt.hft-stuttgart.de/about/publications/

### 3.4 Web Services

**3.4.1 OGC 3DTiles and Quantised Mesh** The system architecture for the urban digital twin leverages OGC-compliant web services to deliver and visualise geospatial data efficiently. 3D Tiles, an OGC community standard, enables streaming of large-scale 3D city models using a hierarchical level-of-detail structure, optimising rendering performance in web-based platforms. CityGML models can be converted to 3D Tiles using open-source/freeware tools like mago-3D-tiler [7], Cesium ion [8] or commercial tools such as Feature Manipulation Engine (FME) [9], preserving GML IDs for integration with Energy ADE 2.0 attributes via a WFS. Quantised Mesh provides compact, high-resolution terrain data, ensuring smooth visualisation with minimal file sizes. Terrain datasets are generated using the open-source Cesium Terrain Builder from TU Munich [10]. Both 3D Tiles and Quantised Mesh are served via an Apache HTTP server, enabling scalable, interactive 3D visualisation in the CesiumJS-based platform for energy data analysis.

**3.4.2 OGC WFS for CityGML Energy ADE 2.0** The OGC Web Feature Service (WFS), a standard for querying geospatial data, enables efficient access to Energy ADE 2.0 attributes within the urban digital twin workflow. In this study, the WFS delivers energy-related data (e.g., heating demands, PV potential) for CityGML-based models stored in 3DCityDB, linking attributes to building geometries via GML IDs. By separating attributes from 3D Tiles, this approach reduces file sizes, enhances performance, and ensures interoperability with external GIS applications. Hosted on an Apache server, the WFS supports dynamic queries, enabling real-time integration with the CesiumJS-based platform and facilitating interactive visualisation of energy metrics for PED assessment.

### 3.5 Additional Tools

**3.5.1 QGIS Plugin for 3DCityDB** The QGIS Plugin for 3DCityDB [11], an open-source tool, integrates QGIS with 3DCityDB, enabling seamless interaction with CityGML data stored in a PostgreSQL/PostGIS database (Agugiaro et al., 2024). It simplifies access to semantic 3D city models for urban planners and GIS practitioners, supporting all CityGML modules (e.g., Buildings, Terrain) and Levels of Detail (LoD0–LoD4). The Layer Loader facilitates loading, exploring, and analysing CityGML data in QGIS's 2D/3D environment, while the Bulk Deleter enables efficient dataset maintenance through spatial and attribute-based filtering. The Package Administrator manages user roles for multi-user access.

[7] https://github.com/Gaia3D/mago-3d-tiler
[8] https://cesium.com/platform/cesium-ion/
[9] https://fme.safe.com/
[10] https://github.com/tum-gis/cesium-terrain-builder-docker
[11] https://github.com/tudelft3d/3DCityDB-Tools-for-QGIS

Support for Energy ADE 2.0 is currently in active development, enhancing energy data integration.

**3.5.2 CityDoctor** CityDoctor [12], an open-source tool developed by the Stuttgart University of Applied Sciences (HFT Stuttgart), ensures the quality of CityGML datasets by automating validation and experimental correction of geometric and semantic errors. Such errors can compromise urban energy simulations, leading to unreliable results (Coors et al., n.d.). CityDoctor validates syntax against CityGML 2.0 standards, checks building geometries (e.g., solid bodies, planar surfaces), and performs semantic plausibility checks (e.g., roof orientation, attribute consistency). In this study, CityDoctor ensures CityGML LoD2 models are error-free for integration with SimStadt and MAPED simulations. By improving data reliability, CityDoctor strengthens the urban digital twin workflow, enabling robust analytics for sustainable urban energy planning.

## 4. Implementation

The proposed system architecture has been implemented and tested in the Nordbahnhofviertel district of Stuttgart, a mixed-use urban area comprising approximately 375 buildings undergoing redevelopment. This area presents a diverse building stock and serves as an ideal testbed for evaluating the potential of achieving PED. The base 3D city model for Nordbahnhofviertel was obtained from the City of Stuttgart's open data portal. The dataset, structured in CityGML and compliant with Level of Detail 2 (LoD2), required minimal pre-processing. Key attributes essential for energy simulation—such as building function and year of construction—were already present and consistently linked to official building identifiers, reducing the need for additional enrichment. The geometries included solid building representations with properly defined bounding surfaces and XLinks. Most semantic and geometric validations were successfully passed using CityDoctor, with only minor corrections made to ensure reliability in subsequent energy simulations. Using this validated dataset, building-level energy simulations were conducted with SimStadt, generating outputs such as heating and cooling demand, electricity use from appliances, domestic hot water demand, and photovoltaic potential from roof and wall surfaces. The results were mapped to the Energy ADE 2.0 schema and stored in a PostgreSQL-based 3DCityDB instance. The building-level outputs were then aggregated by building typology and spatial unit (urban function area), enabling district-scale analysis.

The integration between SimStadt and MAPED follows a structured workflow (Figure 2 - See Appendix), developed to ensure seamless data exchange and aggregation. Initially, 3DCityDB was set up with the appropriate CityGML tables and coordinate reference system. The Energy ADE schema was registered within the database, allowing it to store energy simulation results in a structured manner. The SimStadt outputs, typically in CSV format, were either mapped to the Energy ADE schema using FME or imported directly into the database tables using a Python script. The enriched CityGML data, containing the simulated energy attributes, was then imported into 3DCityDB. To enable MAPED to access and process the simulation results, database views were created that aggregate energy indicators from the Energy ADE tables. MAPED, installed as a separate schema in the same PostgreSQL database, queries these views to perform scenario-based analysis at the district scale. The simulation assesses whether current energy demand—under existing building, demographic, and technology conditions—can be met through local renewable energy production.

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

## 5. Preliminary Results

For Nordbahnhofviertel, MAPED confirmed that the district does not yet achieve a positive annual energy balance, indicating that further interventions are required to reach PED status. The MAPED results, including annual energy balances and sector-specific emissions, are written back to the database and linked spatially via gml: IDs of urban function areas. These outputs are then made available through the urban digital twin application (Figure 3 - See Appendix) currently being developed in this study. The 3D visualisation environment—powered by CesiumJS and supported by OGC WFS and 3D Tiles — allows stakeholders to interactively explore scenario results, compare strategies, and evaluate potential interventions, such as retrofitting, renewable integration, and demand-side management.

## 6. Conclusion and Future Work

In conclusion, this study demonstrates the effective integration of building- and district-scale simulation tools — SimStadt and MAPED — within a CityGML-based urban digital twin platform to assess the Positive Energy District (PED) potential of urban areas. The proposed workflow combines standardised 3D city models, the Energy ADE 2.0 data model, open-source/freeware simulation tools, and web-based visualisation services to enable a seamless transition from data acquisition to scenario-based decision support. This modular and transparent approach not only evaluates current energy performance but also supports the exploration of future energy pathways, guiding cities toward more sustainable and resilient energy systems through evidence-based planning. The Nordbahnhofviertel district in Stuttgart serves as a proof of concept for the framework, which is currently being applied to additional urban districts in Vienna (Grätzl Neu+), Rotterdam (Prinsenland and Feijenoord), and Wrocław (Kleczków). These ongoing applications demonstrate the pipeline's portability and adaptability across diverse urban contexts. The entire system is grounded in open standards (OGC CityGML, Energy ADE 2.0, 3D Tiles, WFS) and utilises open-source or freely available tools (SimStadt, MAPED, CityDoctor, 3DCityDB), ensuring transparency, reproducibility, and long-term sustainability. Future work will focus on extending the digital twin platform to support energy flexibility scenarios by incorporating dynamic factors such as behavioural change, energy storage, and grid interaction. This will allow assessment of how PED targets can be achieved under varying future conditions and planning constraints.

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## References

Agugiaro, G., Benner, J., Cipriano, P., Nouvel, R., 2018. The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations. *Open Geospatial Data, Software and Standards*.

Agugiaro, G., Padsala, R., 2025. A proposal to update and enhance the CityGML Energy Application Domain Extension. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, same volume as this paper.

Agugiaro, G., Pantelios, K., León-Sánchez, C., Yao, Z., Nagel, C., 2024. Introducing the 3dcitydb-tools plug-in for qgis. *Recent Advances in 3D Geoinformation Science*.

Akahoshi, K., Ishimaru, N., Kurokawa, C., Tanaka, Y., Oishi, T., Kutzner, T., Kolbe, T. H., 2020. I-URBAN REVITALIZATION: CONCEPTUAL MODELING, IMPLEMENTATION, AND VISUALIZATION TOWARDS SUSTAINABLE URBAN PLANNING USING CITYGML. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, V-4-2020.

Batty, M., 2024. Digital twins in city planning. *Nature Computational Science*.

Coors, V., Betz, M., Duminil, E., n.d. A Concept of Quality Management of 3D City Models Supporting Application-Specific Requirements. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 88.

Coors, V., Gutbell, Koukofikis, Mohammed, S., O'Mahony, Jacovella-St-Louis, Ryden, S., 2018. Ogc testbed-13: 3d tiles and i3s interoperability and performance er. Open Geospatial Consortium. http://www.opengis.net/doc/PER/t13-NG002.

Coors, V., Padsala, R., 2024. Urban Digital Twins Empowering Energy Transition: Citizen-Driven Sustainable Urban Transformation towards Positive Energy Districts. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-4/W10-2024.

Derkenbaeva, E., Halleck-Vega, S., Jan-Hofstede, G., Van-Leeuwen, E., 2022. Positive energy districts: Mainstreaming energy transition in urban areas. *Renewable and Sustainable Energy Reviews*, 153.

European Commission, 2020. POSITIVE ENERGY DISTRICTS SOLUTION BOOKLET.

Kutzner, T., Chaturvedi, K., Kolbe, T. H., 2020. CityGML 3.0: New Functions Open Up New Applications. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 88.

Lei, B., Janssen, P., Stoter, J., Biljecki, F., 2023. Challenges of urban digital twins: A systematic review and a Delphi expert survey. *Automation in Construction*, 147.

McGookin, C., Ó Gallachóir, B., Byrne, E., 2021. Participatory methods in energy system modelling and planning – A review. *Renewable and Sustainable Energy Reviews*, 151.

Neumann, H.-M., Hainoun, A., Stollnberger, R., Etminan, G., Schaffler, V., 2021. Analysis and Evaluation of the Feasibility of Positive Energy Districts in Selected Urban Typologies in Vienna Using a Bottom-Up District Energy Modelling Approach. *Energies*, 14.

Nouvel, R., Brassel, K.-H., Bruse, M., Duminil, E., Coors, V., Eicker, U., Robinson, D., 2015. Simstadt, a new workflow-driven urban energy simulation platform for citygml city models. *CISBAT 2015*.

Padsala, R., Fink, T., Peters-Anders, J., Gebetsroither-Geringer, E., Coors, V., 2020. From urban design to energy simulation – a data conversion process bridging the gap between two domains. *SHAPING URBAN CHANGE – Livable City Regions for the 21st Century. Proceedings of REAL CORP 2020, 25th International Conference on Urban Development, Regional Planning and Information Society*.

Padsala, R., Gebetsroither-Geringer, E., Peters-Anders, J., Coors, V., 2021. INCEPTION OF HARMONISING DATA SILOS AND URBAN SIMULATION TOOLS USING 3D CITY MODELS FOR SUSTAINABLE MANAGEMENT OF THE URBAN FOOD WATER AND ENERGY RESOURCES. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, VIII-4/W1-2021.

Reber, A., Simon-Philipp, C., Prajapati, M., Padsala, R., Coors, V., 2025. Hybride Partizipation für eine bürgergetragene Energiewende. *Transforming Cities*, 10.

Rosser, J., Long, G., Zakhary, S., Boyd, D., Mao, Y., Robinson, D., 2019. Modelling Urban Housing Stocks for Building Energy Simulation Using CityGML EnergyADE. *ISPRS International Journal of Geo-Information*.

Rossknecht, M., Airaksinen, E., 2020. Concept and Evaluation of Heating Demand Prediction Based on 3D City Models and the CityGML Energy ADE — Case Study Helsinki. *ISPRS International Journal of Geo-Information*.

Santhanavanich, T., Padsala, R., Rossknecht, M., Dabirian, S., Saad, M. M., Eicker, U., Coors, V., 2023. ENABLING INTEROPERABILITY OF URBAN BUILDING ENERGY DATA BASED ON OGC API STANDARDS AND CITYGML 3D CITY MODELS. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, X-1/W1-2023.

Weil, C., Bibri, S. E., Longchamp, R., Golay, F., Alahi, A., 2023. Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities. *Sustainable Cities and Society*.

Würstle, P., Santhanavanich, T., Padsala, R., Coors, V., 2021. DEVELOPMENT OF A DIGITAL 3D PARTICIPATION PLATFORM - CASE STUDY OF WEILIMDORF (STUTTGART, GERMANY). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVI-4/W1-2021.

Zhang, X., Shen, J., Saini, P., Lovati, M., Huang, P., Huang, Z., 2021. Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications. *Frontiers in Sustainable Cities*, 3.

## Appendix

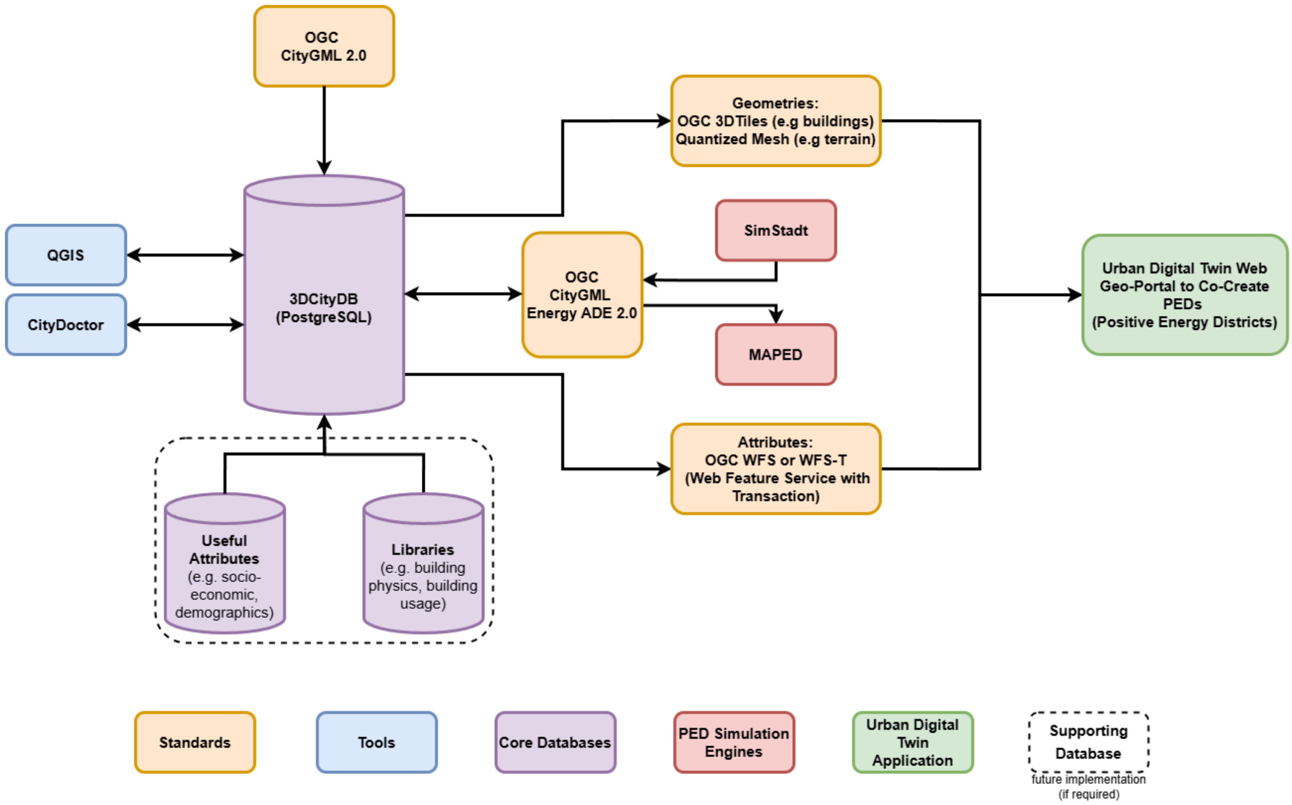


Figure 1. Modular system architecture for an urban digital twin built on open standards to evaluate PED potential

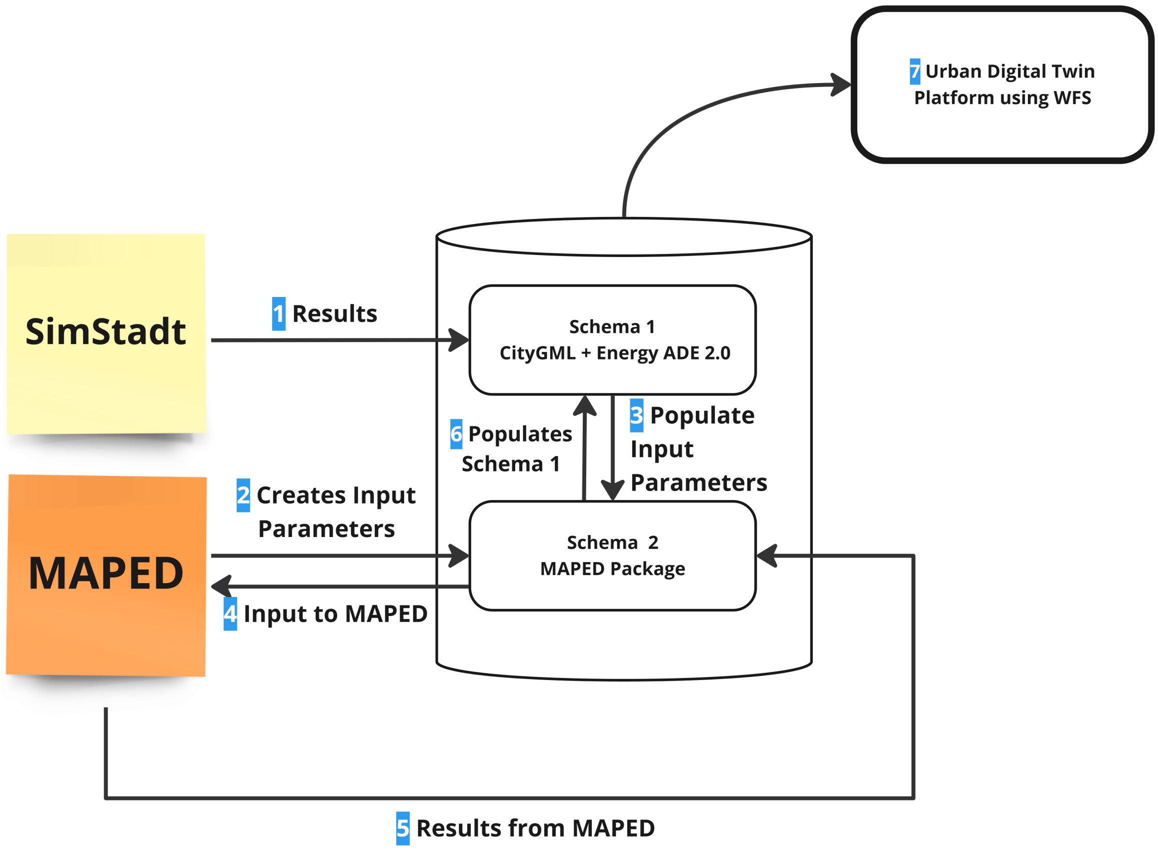


Figure 2. Data flow and schema interaction between SimStadt and MAPED via Energy ADE 2.0

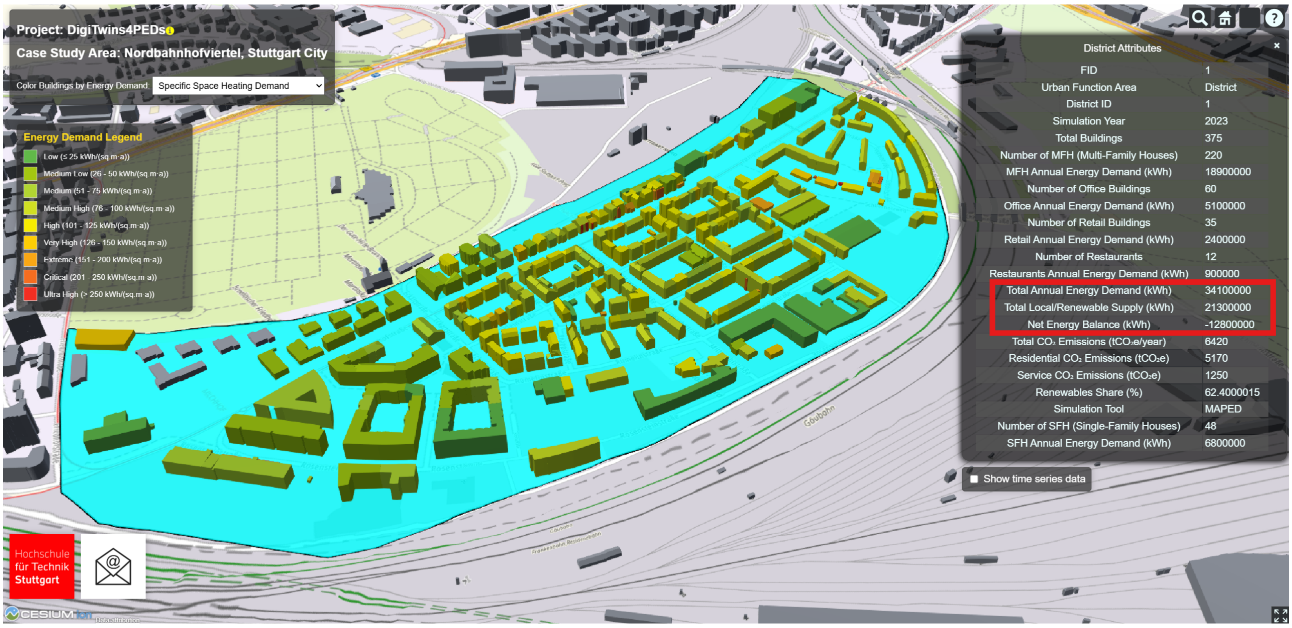


Figure 3. Urban digital twin viewer built using OGC standards