3DxVERSE

Work Package 8

D8.1: Digital twin for sustainable living communities and energy transition: first report

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
3DxVERSE	EU project on Local and System-of-Systems Digital Twins for sustainable living communities and sustainable travel.
AHN	*Actueel Hoogtebestand Nederland:* Dutch national elevation model used for terrain and height data.
AI	Artificial Intelligence: techniques for data-driven analysis, prediction and optimisation.
API	Application Programming Interface: standardised interface for systems to exchange data and functions.
AR	Augmented Reality: technology overlaying digital information on the real world.
BAG	*Basisregistratie Adressen en Gebouwen:* Dutch national register of addresses and buildings used for geometry and attributes.
B1	Language level B1: plain-language reading level used for accessible public communication.
BEMS	Building Energy Management System: system that monitors and controls building energy use and indoor climate.
CAPEX	Capital Expenditure: upfront investment costs for assets such as retrofits or infrastructure.
CBS	*Centraal Bureau voor de Statistiek:* Statistics Netherlands; provides official data on energy, demographics and economy.
Cesium / CesiumJS	Open web-based 3D geospatial platform used for visualising the Local Digital Twin.
CI/CD	Continuous Integration / Continuous Deployment: DevOps practices for frequent, automated software testing and deployment.
CityGML	City Geography Markup Language: OGC standard for semantic 3D city models.
CityJSON	JSON-based encoding of CityGML 3D city models.
CO_2	Carbon dioxide: greenhouse gas used as the main indicator for emissions and climate impact.
CSV	Comma-Separated Values: simple text format for exchanging tabular data.
CPO	Charge Point Operator: organisation operating public or semi-public EV charging infrastructure.
D8.1 / D8.2 / D8.4	Deliverables 8.1, 8.2, 8.4: WP8 reports on implementation, evaluation and replication.
DevSecOps	Development, Security and Operations: approach that integrates security into the entire software lifecycle.
DID	Decentralised Identifier: cryptographically secure identifier used for self-sovereign digital identities.
DPIA	Data Protection Impact Assessment: GDPR-required assessment of privacy risks and mitigation measures.
DSO	Distribution System Operator: company operating local electricity and gas distribution grids.
EC	European Commission: executive body of the European Union and addressee of the deliverable.
EDIC	European Digital Infrastructure Consortium : EU instrument for joint digital infrastructure initiatives (e.g. CitiVerse EDIC).
EIRA	European Interoperability Reference Architecture: EU reference for interoperable public-sector IT systems.

EIF	European Interoperability Framework: EU framework for interoperability across public administrations.
EMS	Energy Management System: monitors, controls and optimises energy flows in a building or district.
EPC	Energy Performance Certificate: official energy label indicating a building's energy efficiency class.
ESCO	Energy Service Company: company delivering energy services (e.g. heat supply) with performance-based contracts.
ESDL	Energy System Description Language: semantic modelling language for describing energy systems and assets.
ESRI	Environmental Systems Research Institute: vendor of the ArcGIS platform used for the LDT testbed.
ESSIM	Energy System Simulation model: simulation environment used for ESDL-based energy system scenarios.
EU	European Union: political and economic union of member states; main policy framework.
EV	Electric Vehicle: vehicle powered by electricity, relevant for charging and grid-load scenarios.
GDPR	General Data Protection Regulation: EU regulation on personal data protection and privacy.
GIS	Geographic Information System: software and methods for managing and analysing spatial data.
GML	Geography Markup Language: XML-based OGC standard for encoding geographic information.
GTS	Gasunie Transport Services: Dutch transmission system operator for high-pressure gas networks.
H_2	Hydrogen: energy carrier used in the Almelo hydrogen micro-network pilot.
H2Hub Twente	Regional initiative for green hydrogen production and applications in the Twente region.
IoT	Internet of Things: network of connected sensors and devices providing real-time data.
IS2H4C	Industrial Symbiosis to Hubs for Circularity: Horizon Europe project linked to hydrogen and industrial symbiosis pilots.
JSON	JavaScript Object Notation: lightweight data format used for APIs and configuration.
JSON-LD	JSON for Linked Data: JSON-based format for expressing linked data with semantic context.
KPI	Key Performance Indicator: quantitative measure used to track technical or social performance.
KNMI	*Koninklijk Nederlands Meteorologisch Instituut:* Royal Netherlands Meteorological Institute; provides weather and climate data.
LDT	Local Digital Twin: digital representation of a local area (e.g. district or city) used for planning and decision-making.
LOD2	Level of Detail 2 - 3D building model level including roof shapes and detailed geometry.
MIMs	Minimal Interoperability Mechanisms: OASC baseline specifications for interoperable city data platforms.
MVP	Minimum Viable Product: first usable version of the LDT for testing and engagement.
NGSI-LD	Next Generation Service Interface, Linked Data: ETSI standard for context information management using linked data.

OASC	Open & Agile Smart Cities: international network of cities defining practical interoperability mechanisms.
ODbL	Open Database License: open licence used for OpenStreetMap and similar datasets.
ODT	*Omgevingsdienst Twente:* regional environmental authority responsible for permits and enforcement.
OGC	Open Geospatial Consortium: standards body for geospatial data and services (e.g. WMS, WFS, CityGML).
OSM	OpenStreetMap: open, crowd-sourced map database used for roads, land use and points of interest.
PED	Positive Energy District: district that produces more renewable energy annually than it consumes.
PDOK	*Publieke Dienstverlening Op de Kaart:* Dutch national geospatial portal providing datasets such as BAG and 3D BAG.
PIA	Privacy Impact Assessment: assessment of privacy impacts; often used together with a DPIA.
PBL	*Planbureau voor de Leefomgeving:* Netherlands Environmental Assessment Agency; provides reference studies (e.g. Startanalyse 2025).
PUB	Public: dissemination level indicating that the deliverable is publicly accessible.
PV	Photovoltaic: solar electricity generation technology (e.g. rooftop solar panels).
RAID	Risks, Assumptions, Issues, Dependencies: log used for structured project risk and issue management.
RES	Renewable Energy Sources: energy from renewable resources such as solar, wind and biomass.
REST	Representational State Transfer: web service style commonly used for HTTP-based APIs.
RVO	*Rijksdienst voor Ondernemend Nederland:* Netherlands Enterprise Agency; provides data and support for energy and sustainability.
SAREF	Smart Applications REFerence Ontology: reference ontology for IoT and energy devices and measurements.
SDGs	Sustainable Development Goals: United Nations global goals for sustainable development to 2030.
SME	Small and Medium-sized Enterprise: smaller businesses; relevant as local partners and suppliers.
TenneT	Transmission system operator for high-voltage electricity networks in the Netherlands and parts of Germany.
TNO	*Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek:* Dutch applied research organisation providing the LDT platform and ESDL expertise.
TSO	Transmission System Operator: company operating high-voltage electricity or high-pressure gas networks.
UT / UTwente	University of Twente: Dutch university involved as knowledge partner in modelling and hydrogen pilots.
V2G	Vehicle-to-Grid: technology allowing EVs to feed electricity back into the grid.
VC	Verifiable Credential: cryptographically signed credential used to prove identity or rights.
VTH	*Vergunningverlening, Toezicht en Handhaving:* Dutch term for permitting, supervision and enforcement.

VR	Virtual Reality: fully virtual 3D environments used for immersive visualisation.
WFS	Web Feature Service: OGC standard for serving vector geospatial features via web APIs.
WMS	Web Map Service: OGC standard for serving map images via web APIs.
WP	Work Package: logical grouping of tasks within the 3DxVERSE project (e.g. WP8 Pilots and Citizen Engagement).
XR/VR	Extended Reality / Virtual Reality: immersive technologies used for advanced visualisation and stakeholder engagement.

EXECUTIVE SUMMARY

The 3DxVERSE project, co-funded by the European Commission, is designed to advance the development of interoperable, secure, and citizen-centric Local Digital Twins (LDTs). These digital twins aim to support the creation of sustainable living communities and to promote smart, sustainable travel and mobility across Europe.

As part of Work Package 8 (WP8), the project moves from design to action, focusing on the operational deployment and validation of these digital twins in real-world environments. This deliverable represents the first major implementation milestone for the "Sustainable Living Communities" theme:

Deliverable D8.1 represents "Digital Twin for sustainable living communities and energy transition: first report"

WP8 serves as the application and validation layer of the 3DxVERSE architecture, translating the frameworks and models developed in earlier work packages (WP3–WP7) into practical tools for pilot locations. This document specifically details the implementation plan for the **Almelo-Aadorp pilot** in the Netherlands.

Deliverable D8.1 focuses on the operational realization of a **Positive Energy District (PED)** in the village of Aadorp. By integrating real-world energy data, 3D city models, and simulation workflows, this deliverable demonstrates how a Local Digital Twin can serve as a socio-technical instrument to drive the energy transition. It connects technical innovation (e.g., hydrogen micro-networks, retrofit scenarios) with inclusive governance, positioning the Almelo pilot as a reference implementation for citizen-led, climate-neutral urban development.

This deliverable provides a detailed roadmap for the Aadorp use case, serving as a blueprint for implementation, governance, and evaluation. Where relevant, the data architectures, engagement strategies, and interoperability patterns defined here are designed to be replicable, supporting cross-pilot learning with other 3DxVERSE sites and contributing to the broader EU Local Digital Twin ecosystem.

Chapter 1: Introduction Chapter 1 establishes the strategic and operational context for Deliverable D8.1. It outlines the purpose of the deliverable as both an implementation roadmap and a pre-evaluation framework, bridging the conceptual design of WP6 with the real-world execution in WP8. The chapter details the interdependencies with other work packages, highlighting how the pilot validates the 3DxVERSE reference architecture, trust frameworks, and data pipelines. It also identifies the intended audience and sets the stage for demonstrating how the Almelo LDT supports evidence-based decision-making and citizen participation.

Chapter 2: Almelo-Aadorp Pilot Overview Chapter 2 provides a overview of the Almelo-Aadorp pilot, set against the backdrop of the Kanaalfront redevelopment. It defines the pilot's core objective: establishing a Positive Energy District (PED) through a combination of demand reduction, renewable generation, and innovative energy carriers like hydrogen. The chapter elaborates on the collaborative governance model, featuring a partnership between the Municipality of Almelo and the Dorpscoöperatie Aadorp, and outlines the roles of key stakeholders including utilities, housing associations, and knowledge partners. This section anchors the digital twin in its local socio-economic context.

Chapter 3: Almelo Local Digital Twin Architecture Chapter 3 details the technical and functional architecture of the Almelo Local Digital Twin. It describes the modular data layer, which fuses 3D spatial data (BAG/3D BAG), building energy attributes, and real-time IoT streams within a GDPR-compliant governance framework. The chapter introduces the suite of analytical models, including energy balance, behavioural adoption, and optimisation models, that power the twin's decision-support capabilities.

Furthermore, it explains the dual-platform approach (ESRI and Open/Cesium) and the interoperability mechanisms (ESDL, MIMs) that ensure the twin is an open, secure, and reusable node within the European digital ecosystem.

Chapter 4: Pilot Implementation Strategy This chapter outlines the structured strategy for deploying the Almelo LDT. It defines seven concrete workstreams ranging from technical validation and interoperability testing to citizen engagement and replication planning. The chapter presents a phased implementation plan-starting with infrastructure setup, moving to scenario testing (e.g., hydrogen and retrofits), and concluding with iterative calibration. By mapping roles, dependencies, and risks, this chapter provides a clear execution guide to transition the LDT from a prototype to a fully operational tool for the energy transition.

Chapter 5: Evaluation Framework and KPIs Chapter 5 establishes the methodology for assessing the impact and performance of the Almelo pilot. It introduces a comprehensive Key Performance Indicator (KPI) framework that covers both technical dimensions (e.g., energy efficiency, CO_2 reduction, renewable share) and social dimensions (e.g., citizen participation, social inclusion, quality of life). The chapter describes the data collection and monitoring procedures required to track progress from the pre-pilot baseline to post-pilot outcomes, ensuring that results are measurable, comparable across 3DxVERSE pilots, and aligned with European sustainability goals.

Chapter 6: Conclusions and Replication Pathway Chapter 6 summarises the key contributions of the deliverable, highlighting how the Almelo pilot successfully operationalises the concept of a citizen-centric PED Digital Twin. It distils preliminary lessons learned regarding governance, open standards, and socio-technical integration. Finally, the chapter outlines the pathway for replication and scaling, describing how the models and methods developed in Almelo will feed into future evaluation tasks (D8.2) and be packaged as reusable assets for other cities and the EU Local Digital Twin Toolbox.

1.INTRODUCTION

1.1 Introduction to 3DxVERSE

The 3DxVERSE project aims to harness the potential of Local and System-of-Systems Digital Twins to foster sustainable living communities and sustainable travel. It focuses on key use cases at different scales, from airports to neighbourhoods and villages, addressing sustainability, economic development, societal well-being, safety, security, resilience, and corporate sustainability responsibility in a holistic way

By establishing interoperable Local Digital Twins and leveraging technologies such as Artificial Intelligence (AI), Extended and Virtual Reality (XR/VR) and data spaces, the project aligns with the New European Bauhaus initiative and the G20 Framework for Systems of Digital Public Infrastructure. It seeks to operationalise these frameworks in real-world urban and regional environments, turning abstract principles into practical tools for planning, governance and citizen engagement.

3DxVERSE collaborates with leading European and international initiatives and organisations, including the International Data Spaces Association, Open & Agile Smart Cities (OASC) and its Minimal Interoperability Mechanisms (MIMs), and emerging European Digital Infrastructure Consortia (EDICs). Through these links, the project aims to deliver a transformative impact on digital inclusion, innovation and sustainability and to contribute to the achievement of the 2030 Agenda for Sustainable Development.

The project’s ambition is to create an open, interoperable, secure, trustworthy, fair and inclusive reference implementation blueprint for Local Digital Twins serving EU citizens, businesses and public administrations. By doing so, 3DxVERSE supports a resilient, inclusive and environmentally conscious digital economy and society. Societal impact, inclusive economic growth and long-term sustainability are central values and closely aligned with the United Nations Sustainable Development Goals (SDGs) and the European Union’s green and digital transition agendas.

To achieve this, 3DxVERSE works with a diverse network of international partners and pioneering cities that are actively shaping the future of digital urban ecosystems. The core pilot sites being Almelo in the Netherlands, Hamburg in Germany, Timișoara in Romania and Oranjestad in Aruba, represent a variety of socio-economic contexts, geographies and governance models. Each site brings specific local challenges and innovative approaches, enriching the project’s scope and reinforcing a shared commitment to interoperable, citizen-centric Local Digital Twins across Europe and beyond.

1.2 Purpose and scope of the Deliverable 8.1

Deliverable D8.1 represents the first full implementation phase of the Local Digital Twin (LDT) for sustainable living communities, with a specific focus on the Almelo-Aadorp pilot. Building on the conceptual frameworks and use cases developed in D6.1 “Sustainable Living Communities” and on the prototype integration work in WP7, this deliverable translates theoretical models, interoperability principles and simulation workflows into an operational implementation plan for the Aadorp Positive Energy District (PED).

Where D6.1 provided the conceptual blueprint for energy communities and D7.1 delivered the first functional prototype of the Almelo Energy Twin, D8.1 demonstrates how these concepts are being operationalised in practice. It does so by integrating real-world energy data, multi-source geospatial layers, building models and citizen-engagement tools within the overarching 3DxVERSE architecture.

D8.1 therefore acts both as an implementation roadmap and as a pre-evaluation framework. It consolidates methods, governance structures and engagement mechanisms that will guide subsequent deliverables in WP8, notably D8.2 (pilot evaluation). In line with the data-to-decision lifecycle illustrated in Figure 1, the deliverable showcases how pilot communities can move from raw data to knowledge, simulation, visualisation, citizen engagement and evidence-based decision-making through iterative digital-twin processes.

Within this context, D8.1 pursues the following key purposes, with Almelo-Aadorp as the primary reference pilot for sustainable living communities:

- **Operational realisation of the Aadorp use case:** documenting the implementation of the Almelo-Aadorp Positive Energy District, including its digital-twin infrastructure, data sources, simulation workflows and stakeholder integration.

- **Integration with interoperability testbeds:** operationalising both the ESRI Local Digital Twin Testbed and the Open Digital Twin Testbed (via Geonovum/iLabs), and demonstrating a dual-stack architecture that supports reusability, openness and data-space compatibility.

- **Governance, trust and privacy-by-design:** applying the WP5 trust and security framework, embedding DevSecOps principles and DPIA/PIA procedures and ensuring GDPR-compliant and transparent data management for the pilot.

- **Simulation and citizen-engagement planning:** defining the simulation environment for energy-transition scenarios and establishing community participation workflows through tools such as StoryMaps and ArcGIS Hub.

- **KPI framework and evaluation preparation:** outlining the technical and social KPIs for the pilot and linking them with the WP6 metrics and overall project sustainability objectives.

- **Feedback and replication pathway:** capturing lessons from Almelo-Aadorp that inform evaluation (D8.2), and enabling cross-city learning with the other pilot sites.

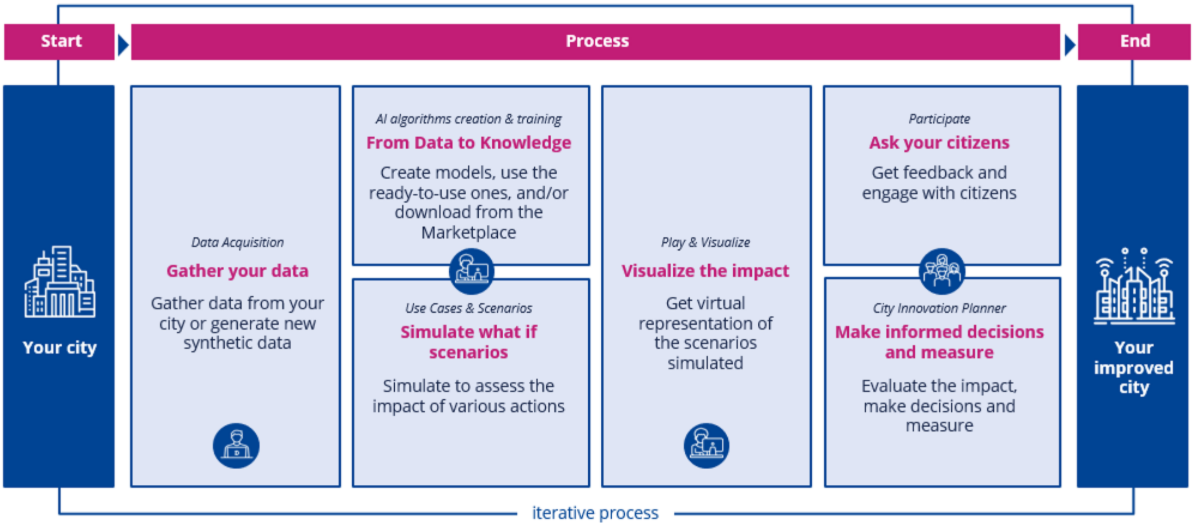

Figure 1: Data-to-Decision Lifecycle

1.3 Relationship with Other Work Packages and Deliverables

Work Package 8 (WP8) - *Pilots and Citizen Engagement* - is positioned at the application and validation layer of the 3DxVERSE architecture. While WPs 3-7 design and develop the underlying architecture, models, data pipelines and trust mechanisms, WP8 brings these building blocks into real pilot environments and assesses their performance, usability and societal impact.

D8.1 is the first major implementation step within WP8. It uses inputs from the technical and governance work packages and provides structured feedback based on pilot deployment. The main interdependencies between WP8 and other WPs are summarised in Table 1.

Table 1: Dependencies between WP8 and other Work Packages

Work Package	Main contribution to WP8	Feedback from WP8 (Pilots)
WP1 - Ethics	Ethical, privacy and consent requirements	Evidence of compliance and citizen-engagement feedback
WP2 - Coordination	Project management, quality assurance and reporting	Pilot progress metrics and RAID (Risks, Assumptions, Issues, Dependencies) updates
WP3 - Interoperability Architecture	Reference models, interoperability patterns, NGSI-LD standards	Validation of architecture, performance and practical applicability
WP4 - Digital Commons	Ethical governance and participation principles	Real-world citizen engagement results and lessons for Digital Commons
WP5 - Trust & Security	iSHARE-based trust, DevSecOps and security frameworks	Implementation evidence, security evaluation and audit trails
WP6 - Use Case Design	Use-case structure, KPIs, datasets and methodological guidance	Operational validation, performance results and refinements to KPI sets
WP7 - Testbed Integration	Technical testbeds, data pipelines and integration environments	Interoperability testing feedback and requirements for improvements
WP9 - Dissemination & Exploitation	Communication channels and dissemination strategies	Pilot visuals, results, stories and lessons learned for external audiences

Through these interactions, D8.1 delivers three types of added value. First, it validates and refines the architecture, interoperability mechanisms and trust frameworks developed upstream. Second, it provides concrete, real-world evidence on how Local Digital Twins support energy transition and citizen participation in Almelo-Aadorp. Third, it prepares a structured knowledge base for the subsequent evaluation and scaling deliverable D8.2, and for the project’s contributions to wider European initiatives such as the EU Local Digital Twin Toolbox and CitiVerse EDIC. The general interaction between the Work Packages is illustrated in Figure 2 below.

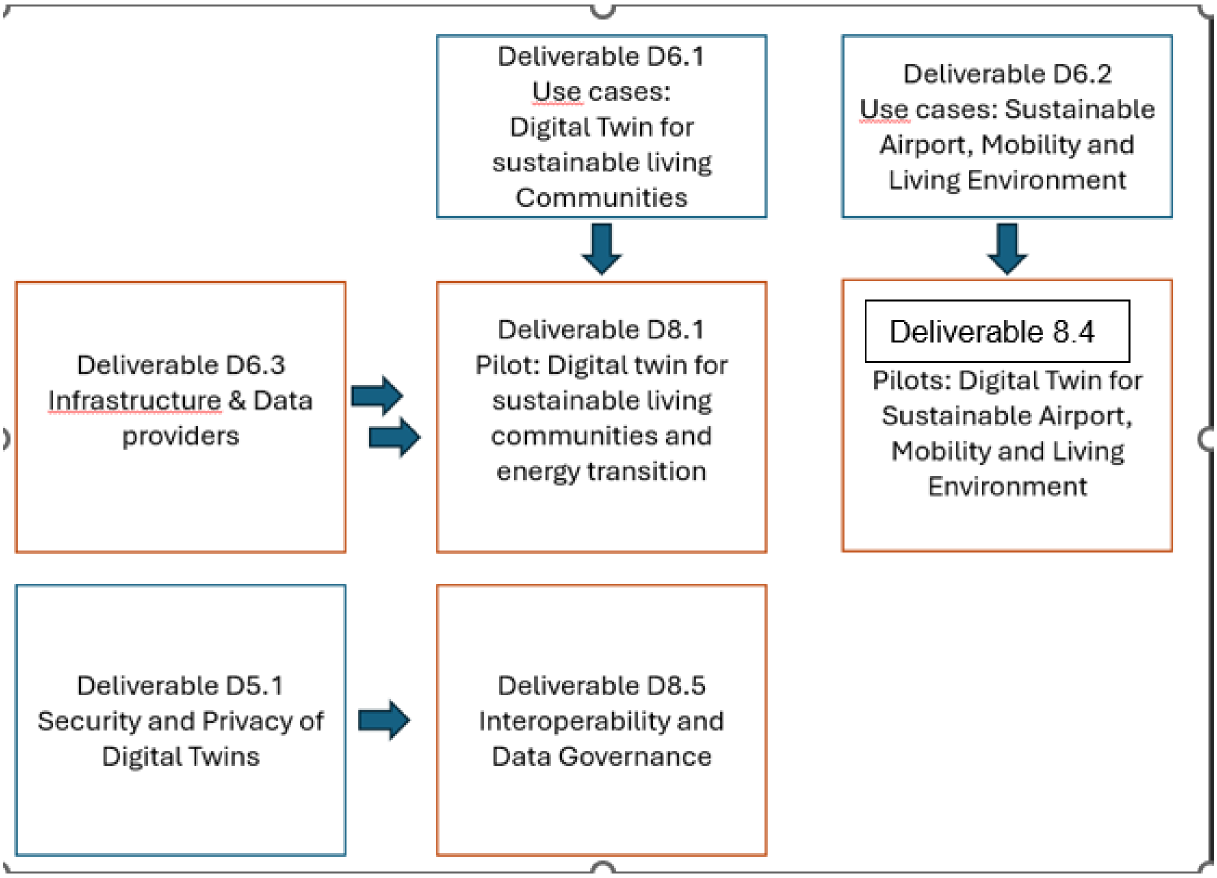

Figure 2: Interdependencies between work packages in the 3DxVERSE project

Interconnected deliverables November 2025 3DxVERSE deliverables give an overview of the actual status of the pilots in the project. The deliverable D6.3 as well as the deliverables D8.1 and D8.4 cover the use cases as specified in the use case documents being D6.1 about the Almelo pilot, and D6.2 about the Mobility and Travel pilots. D6.3, D8.1 and D8.4 documents effectively describe the data sources and how the data will be handled technically.

D6.3 is based on the deliverable D3.1 about the Reference Architecture and is more structural and covering all use cases, D8.1 details the Almelo pilot and D8.4 details the Mobility and Travel Pilots and cover the separate use cases of these pilots. Deliverable D8.5 describes the governance layer although D8.1 and D8.4 also touch on the governance for their specific use-cases.

The deliverable D8.5 about the interoperability and governance is based on the deliverable D5.1 (Security and Privacy of Digital Twins), which in itself is based on deliverable D1.1 (Ethics Framework) and D4.1 (Digital Commons Framework). Taken together, these documents describe the operationalization 3DxVERSE architectures and governance in the pilots. The diagram below illustrates this with November 2025 deliverables highlighted in red and their primary antecedents in blue boxes.

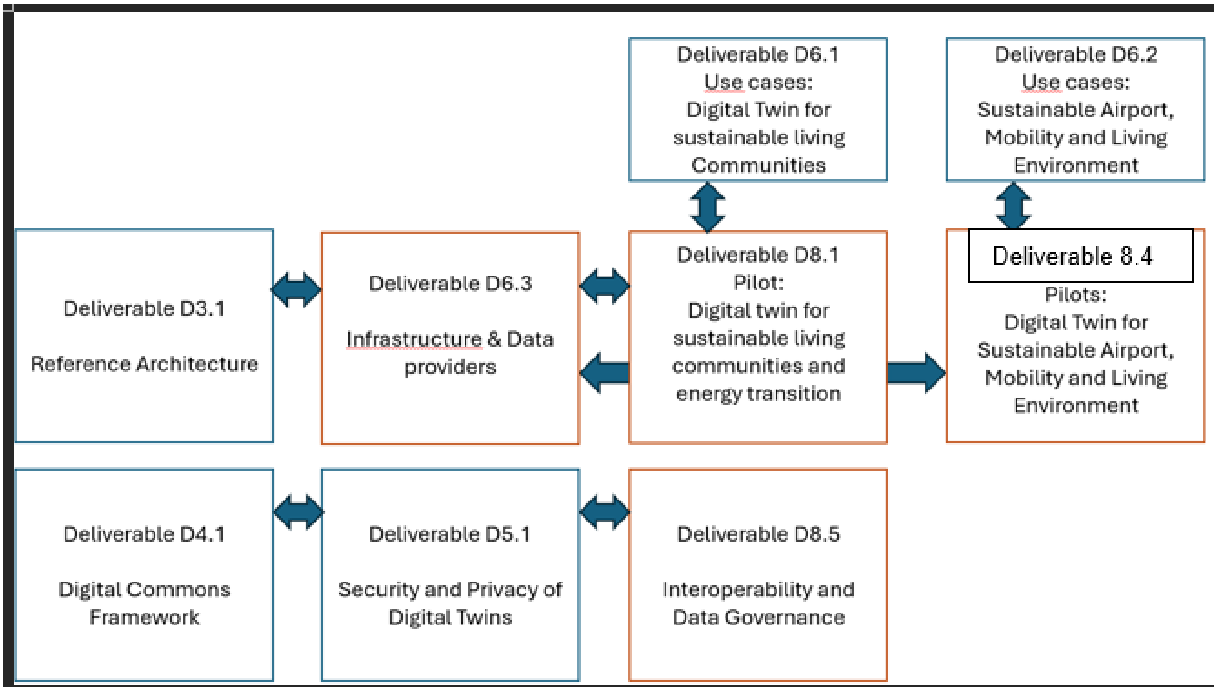

Figure 3: Relationship between interconnected deliverables (November 2025)

1.4 Intended audience

The dissemination level of Deliverable D8.1 is *Public* (PUB). The document is available to all 3DxVERSE beneficiaries, to the services of the European Commission (EC) and to external stakeholders interested in Local Digital Twins, Positive Energy Districts and citizen-centred digital infrastructure.

The primary audience includes:

- governance bodies within 3DxVERSE (General Assembly, Steering Committee, Technical Management Team, Advisory Board);
- technical partners working on architecture, interoperability, data governance and modelling;
- local and regional authorities, utilities, cooperatives and community organisations engaged in PED and digital-twin initiatives;
- European stakeholders involved in CitiVerse **and other CitiVerse projects (for co-learning)**, the EU Local Digital Twin Toolbox and related Digital Europe and Green Deal actions.

To support these diverse audiences, the document is structured as follows:

- **Chapter 1** introduces the 3DxVERSE vision, explains the purpose and scope of D8.1, clarifies its relationship with other work packages and summarises the objectives.
- **Chapter 2** provides an overview of the Almelo-Aadorp pilot, including local context, use-case definition, governance arrangements and stakeholder roles.
- **Chapter 3** presents the Almelo Local Digital Twin architecture, covering data sources and governance, analytical models and simulations, platform and user interfaces, and interoperability and trust mechanisms.

- **Chapter 4** outlines the pilot implementation strategy, including objectives, workstreams, phased deployment and links to future project phases.

- **Chapter 5** describes the evaluation framework and KPI matrix for the Almelo-Aadorp pilot, together with the methodology for monitoring and comparison across pilots.

- **Chapter 6** summarises key conclusions and lessons and outlines the replication pathway and next steps within 3DxVERSE.

1.5 Objectives of the Deliverable 8.1

The main objective of Deliverable D8.1 is to demonstrate and prepare the deployment of the Almelo-Aadorp Local Digital Twin as a reference implementation for sustainable living communities. It aims to validate how Digital Twin ecosystems can contribute to energy transition, citizen participation and inclusive local governance through secure, interoperable and ethical data use.

More specifically, D8.1 pursues the following high-level objectives:

1. **Implement and validate the Almelo-Aadorp Local Digital Twin:**
    - deploy a functioning PED digital twin that integrates building, energy and environmental datasets with simulation and visualisation tools;
    - ensure that the LDT represents key real-world infrastructures and transition pathways in Aadorp, including district heating concepts, the hydrogen micro-network, rooftop PV and the Kanaalfront redevelopment area.
2. **Demonstrate interoperability across testbeds and platforms:**
    - integrate the ESRI Local Digital Twin Testbed and the Open Digital Twin Testbed into a dual-stack solution;
    - show that data, models and scenarios can be exchanged and reused across proprietary and open-source environments in line with EU interoperability and data-space ambitions.
3. **Operationalise trust, security and data governance frameworks:**
    - apply the 3DxVERSE trust and security framework, including DevSecOps principles and GDPR-compliant data protection;
    - define and document a data-governance model for the pilot, covering open-data policies, licensing, consent and audit trails.
4. **Develop and calibrate simulation and decision-support models:**
    - implement and calibrate energy, behavioural, optimisation and environmental models that support evidence-based planning for the Aadorp PED;
    - link these models to user-facing tools, including expert dashboards and interactive “what-if” interfaces for residents and planners.
5. **Prepare evaluation through a KPI framework and monitoring approach:**
    - define KPIs covering technical performance, sustainability, participation, trust and interoperability, consistent with the WP6 framework;
    - design a monitoring and comparison approach that allows pre-pilot, mid-pilot and post-pilot assessment and cross-pilot learning.
6. **Strengthen citizen engagement and inclusive governance:**
    - embed co-design, participatory workshops and accessible digital interfaces into the pilot;
    - ensure that twin-enabled decision-making processes are transparent and inclusive for diverse community groups in Aadorp.
7. **Capture lessons and recommendations for replication and scaling:**
    - document insights from implementation and engagement to inform D8.2 (evaluation);
    - formulate recommendations and reusable components that can support other municipalities and pilots in Europe aiming to develop Positive Energy District twins.

The following chapters elaborate how these objectives are operationalised in the Almelo-Aadorp context and how D8.1 connects the design and modelling work of WP6/WP7 with the community implementation and trust frameworks, while feeding validated methods back into the architecture and governance work packages of 3DxVERSE

2. ALMELO-AADORP PILOT OVERVIEW

2.1 Local Context and PED Use Case

2.1.1 Context and Scope

The Almelo-Aadorp pilot is set in the village of Aadorp, within the municipality of Almelo (the Netherlands). The pilot focuses on the Kanaalfront redevelopment area, which is being transformed into a new, green and social “village heart” around the canal. This area functions as a socio-technical living lab, where physical redevelopment (buildings, public space and energy infrastructure) and digital innovation (Local Digital Twin, citizen engagement tools) are developed in parallel.

The living lab is anchored in local ambitions laid down in the *Dorpsambitieplan Aadorp 2022-2030*. This plan emphasises co-design (“aanpak van onderop”), long-term liveability and energy transition, and is implemented in close collaboration between the municipality and the Dorpscoöperatie Aadorp, the village residents’ cooperative.

2.1.2 Positive Energy District Concept and Main Objective

The core ambition of the Almelo-Aadorp pilot is to establish an integrated Positive Energy District (PED). In line with EU usage, a PED is a neighbourhood which, over the course of a year, produces more renewable energy than it consumes, while remaining affordable and comfortable for residents.

The main objective of the pilot is therefore to design and implement a local energy system and redevelopment pathway in which:

- energy demand is significantly reduced through deep renovation and behavioural measures;
- local renewable generation (primarily solar PV) is deployed at scale;
- innovative energy carriers and storage systems support flexibility, resilience and seasonal balancing.

This objective is operationalised through the Almelo Local Digital Twin (LDT), which serves as an “urban sandbox” to combine technical data, social input and planning scenarios for the PED transition (Eurocities, 2024**)**.

2.1.3 Transition Pathway and Timeline

The PED transition is staged along a 2025-2030 pilot roadmap, in which three core technical interventions are combined:

1. **Demand Reduction**
    - Deep energy retrofits of existing homes (insulation, glazing, building envelope measures).
    - Improved control and awareness using smart meters, building automation and feedback from the LDT.

2. **Renewable Generation**
    - Deployment of rooftop solar PV on private and public buildings.
    - Deployment of small scale wind turbines.
    - Exploration of shared/collective production models where feasible (e.g. cooperatively owned PV/wind).
3. **Innovative Energy Carriers and Storage**
    - A green hydrogen pilot (approximately 70 kW electrolysis) linked to the H2Hub Twente initiative, supplying a hydrogen micro-network of four connected addresses for space heating.
    - Integration of batteries and/or thermal storage to support peak shaving and flexibility.

The Local Digital Twin provides the common environment where these interventions are designed, simulated, compared and monitored over time. It allows stakeholders to explore different sequencing and combinations of measures, and to quantify their expected effects on energy, CO_2, comfort and cost.

2.1.4 EU and Policy Alignment

The Almelo-Aadorp pilot is explicitly aligned with broader European and national policy frameworks:

- At EU level, the pilot follows the principles of Living-in.EU, the CitiVerse EDIC (European Digital Infrastructure Consortium for Local Digital Twins), the New European Bauhaus (NEB) and the emerging EU Local Digital Twin Toolbox.

- At national and regional level, it supports Dutch energy and climate goals, including the heat transition in the built environment and regional PED ambitions, in coordination with the Province of Overijssel.

By structuring the Almelo LDT and PED implementation around open standards, interoperable data and citizen engagement, the pilot is designed as a local exemplar that can feed into European guidance and reusable assets for other cities and regions.

Delivering an inclusive PED in Almelo requires a multi-actor coalition with clearly defined roles, responsibilities and engagement processes. The governance model is built on a partnership between the Municipality of Almelo, the Dorpscoöperatie Aadorp and a broader network of utilities, housing providers, knowledge partners and technology providers.

2.2 Governance and Stakeholders

2.2.1 Governance Model

The pilot operates under a collaborative governance model, in which:

- The Municipality of Almelo acts as the primary enabler and accountable public authority for spatial planning, sustainability and mobility.

- The Dorpscoöperatie Aadorp U.A. represents the local community and functions as co-designer, liaison and watchdog for community interests.

- A joint project team for the Kanaalfront development has been established, including:

- the municipal project leader;

- the *wijkregisseur* (neighbourhood liaison) for Aadorp;

- a representative of the Dorpscoöperatie.

The guiding principle for all stakeholder interactions is *“transparantie en participatie gedurende het proces”* (transparency and participation throughout the process) (Gemeente Almelo, 2023). This principle is operationalised through regular co-design activities, open communication channels and clear documentation of decisions and underlying data.

2.2.2 Key Stakeholder Groups and Roles

The key stakeholder groups in the Almelo-Aadorp pilot and their roles are summarised below.

- **Local Community & Citizens**
  Represented by Dorpscoöperatie Aadorp U.A., residents are primary co-creators in the pilot. They participate in co-design workshops, surveys and pilot programmes (e.g. retrofit campaigns), and provide local knowledge and preferences which are embedded in the LDT scenarios.

- **Municipality of Almelo**
  The municipality is the enabler, regulator and accountable body for public goals. It leads spatial planning, sustainability and mobility policies, provides project leadership and resources, and coordinates with the Province of Overijssel and other public authorities for regulatory alignment and potential co-financing.

- **Energy Sector Partners**

- **Cogas** participates as a utility partner for specific energy interventions, such as hydrogen infrastructure or community batteries.

- **Coteq Netbeheer** (DSO) is responsible for local grid operations and capacity planning to accommodate new loads (heat pumps, EV charging, electrolysis).

- Other partners (e.g. local energy cooperatives, ESCOs) may be responsible for implementing and operating concrete energy solutions, such as solar roofs, wind turbines or storage assets.

- **H2Hub Twente and Hydrogen Partners**
  The H2Hub Twente consortium is responsible for the design, build and operation of the green hydrogen pilot. The Water Board (Waterschap Vechtstromen) is consulted regarding reuse of by-products such as oxygen and water, and for alignment with surface water and climate adaptation goals (H2Hub Twente, z.d.).

- **Housing and Built Environment Actors**
  Housing associations (*wooncorporaties*) and private homeowners are responsible for executing retrofits at building level. Developers and architects for the Kanaalfront new-build area are held accountable by the municipality for meeting PED standards. Safety and compliance actors (fire brigade, environmental agency) are consulted on all plans.

- **Knowledge and Technology Partners**

- TNO provides the LDT platform component ESDL-based interoperability model.

- Academic partners such as the University of Twente and Saxion University of Applied Sciences contribute to monitoring, analysis and KPI design.

- The pilot aligns with standards from organisations such as OASC and contributes lessons and artefacts to the EU Local Digital Twin Toolbox and CitiVerse initiatives.

Together, these stakeholders ensure that the Almelo-Aadorp pilot is technically robust, politically anchored and socially legitimate.

2.2.3 Engagement Plan and Channels

To put the principle of "transparantie en participatie" into practice, a multi-channel engagement plan is implemented, tailored to the needs of each stakeholder group:

- Residents and Local Businesses

  - Hands-on co-design workshops using LDT visualisations (2D/3D views, scenario maps).
  - "Street-level" events such as walk-and-talk sessions around Kanaalfront.
  - Regular updates through the *Aadorp.info* website, newsletters and other local communication channels, using accessible (B1-level) language.

- Institutional Partners (Municipality, DSO, Water Board, Housing Associations)

  - Standing monthly coordination meetings to align on permits, technical requirements, data standards and phasing.
  - Thematic technical workshops on interoperability, data governance and evaluation.

- Governance Authorities and Investors (Municipal Council, Province, Banks/Funds)

  - Quarterly progress updates with KPI dashboards and risk (RAID) overviews.
  - Presentation of key choices and trade-offs supported by LDT scenarios.

- Wider Public and Education Stakeholders

  - Public-facing dashboards and StoryMap-style narratives that explain the PED and LDT in simple terms.
  - Potential educational activities in cooperation with schools and community organisations.
  - An online interactive map (via the LDT portal) where ideas, concerns and suggestions can be submitted.

Stakeholders are classified as Core (co-creators/decision-makers, such as Dorpscoöperatie Aadorp) or Consultative (reviewers/advisors, such as the Province) for each project phase. A living stakeholder contact sheet is maintained and updated as the pilot progresses from concept to implementation and evaluation.

2.2.4 RACI Overview by Workstream

The pilot's governance model is further clarified through a RACI matrix, specifying who is Responsible, Accountable, Consulted and Informed for each workstream. This ensures transparency and supports coordination across organisations.

For a detailed breakdown of stakeholder roles and responsibilities per workstream, please refer to the full RACI matrix in **Appendix A**.

This structured allocation of roles helps to avoid gaps or overlaps and ensures that decision-making processes are traceable and accountable.

2.2.5 External Actors in the Local Energy and Infrastructure System

Beyond the core pilot partners, a range of external actors operate critical infrastructures that must be considered in PED design and LDT modelling. For a detailed breakdown of external actors and roles in the local energy and infrastructure system please refer to the table in Appendix B.

These actors are engaged as needed during planning and implementation, and their constraints and opportunities are represented in the LDT's data layers and scenarios.

2.3 Role of the Almelo Pilot in 3DxVERSE

Within 3DxVERSE, the Almelo-Aadorp pilot serves as a reference implementation for Local Digital Twins in sustainable living communities and Positive Energy Districts. It provides a concrete testbed for:

- integrating geospatial, energy, behavioural and governance models into a coherent LDT;
- demonstrating how open standards and dual-stack (ESRI + open) architectures can be used in real municipal settings;
- embedding citizen engagement, data governance and trust-by-design principles in everyday planning processes.

The Almelo experience is designed to be transferable. Lessons, models and software components developed here will inform:

- cross-pilot learning with the other 3DxVERSE sites (Hamburg, Timișoara, Oranjestad), enabling comparisons across different geographies and institutional settings;
- contributions to the EU Local Digital Twin Toolbox, including example datasets, ESDL models, KPIs and engagement patterns;
- guidance for other Dutch and European municipalities that aim to develop PEDs and Local Digital Twins in line with CitiVerse EDIC and Digital Europe initiatives.

In this way, the Almelo-Aadorp pilot is not only a local project but also a building block in a broader European ecosystem of interoperable, citizen-centred digital twins for the energy transition.

3. ALMELO LOCAL DIGITAL TWIN ARCHITECTURE: DATA, MODELS, PLATFORM AND GOVERNANCE

3.1 Conceptual Architecture and Position in 3DxVERSE

The Almelo-Aadorp Local Digital Twin (LDT) is designed as a modular, standards-based architecture that connects heterogeneous datasets, analytical models and user interfaces into a single decision-support environment for the Positive Energy District (PED) transition.

Within the overall 3DxVERSE reference architecture, the Almelo LDT sits at the city-scale application layer, interfacing with:

- **Foundational services and data pipelines** developed in WP3 and WP7 (ingestion, storage, interoperability testbeds).
- **Analytical and simulation capabilities** developed in WP6 and WP7 (energy, behavioural, optimisation and impact models).
- **Trust, security and Digital Commons frameworks** developed in WP4 and WP5 (ethics, governance, data protection, DevSecOps).

Conceptually, the Almelo LDT is organised into four main layers:

1. **Data layer** - combines static and dynamic datasets across geospatial, energy, socio-demographic, sensor/IoT and infrastructure domains.
2. **Model layer** - encapsulates energy, behavioural, optimisation and co-benefit models that transform data into insights.
3. **Platform and UI layer** - delivers expert dashboards and public-facing interfaces in both ESRI and open (Cesium-based) environments.
4. **Governance and trust layer** - ensures interoperability, security, privacy and ethical use of the LDT and its outputs.

This structure allows Almelo to act as a reference implementation for how Local Digital Twins can be configured for sustainable living communities, while remaining compatible with the broader 3DxVERSE system-of-systems vision and European initiatives such as the EU Local Digital Twin Toolbox and CitiVerse EDIC.

3.2 Data Architecture and Sources

This chapter in D8.1 specifically details the data sources and architecture applied within the Almelo-Aadorp pilot context.

The Almelo-Aadorp LDT fuses static baseline data (e.g. 3D city models, building attributes, demographics) with dynamic data streams (e.g. IoT, energy meters, weather) in a modular architecture aligned with the 3DxVERSE interoperability principles (D3.1).Furthermore a structural overview of the data infrastructure, data providers and technical handling across all 3DxVERSE use cases is provided in Deliverable D6.3 (Infrastructure & Data providers).

3.2.1 3D Spatial Data and Base Maps

A detailed 3D city model provides the spatial backbone of the twin. Key elements are:

- Building geometry and attributes from Dutch open data, in particular BAG and 3D BAG (via PDOK), complemented by municipal base maps.
- Pre-processing in QGIS to harmonise footprints, heights and attribute schemas, and to generate a consolidated building layer with energy-related fields.
- For 3D representation, LOD2 building tiles in CityJSON format (3D BAG) are processed via FME to:
  - integrate attributes.
  - reproject geometries.
  - convert CityJSON to CityGML.

The resulting models are stored in 3D CityDB and published as Cesium-ready 3D Tiles, aligned with OGC CityGML/CityJSON standards (3D geoinformation research group, z.d.) and INSPIRE schemas. Future Kanaalfront designs from the architectural firm (e.g. SketchUp models) can be imported into the same base model, enabling comparison of design options and cross-city interoperability and updates (Lehtola et al., 2022**)**.

3.2.2 Building Energy Data

Each building in the twin is enriched with energy-related attributes that support baseline assessment and scenario modelling. Principal sources include:

- **CBS / National Geo-register**: tabular data (CSV) on energy consumption and official energy labels.
- **Municipal programmes**, such as the *Warmteprogramma Almelo*, and utility/ESCO data for district heating where available.
- **Solar potential layers** from national or regional sources (e.g. RVO, municipal studies), often in raster (GeoTIFF) format.
- **A HomeFile**, a voluntary, non-commercial online tool that helps households and energy coaches create a personalised home sustainability plan, while keeping users in control of their data.

These public and private datasets are joined to BAG geometry in QGIS, producing a combined shapefile with geometry, energy label and consumption fields. Machine-learning models in Python are used to estimate missing attributes (e.g. insulation levels, window type, heating system) and to create a complete building-level dataset stored as CSV for further modelling. Baseline parameterisation is aligned with national studies such as the PBL *Startanalyse 2025* and local municipal plans.

3.2.3 Demographic and Social Data

Demographic and social data help to understand who lives in the area and how different groups may adopt retrofit and energy measures. respecting GDPR **and in full compliance with the 3DxVERSE privacy policy**, only aggregated and pseudonymised data are used, including:

- Community-level socio-demographic indicators (household type, income bands, age structure, tenure) from official statistics and municipal sources at appropriate spatial aggregation levels.
- Results from co-design workshops and surveys for the Kanaalfront, capturing preferences, perceived barriers and ideas for measures. These are stored as pseudonymised tabular data (CSV) with direct identifiers removed and analyses conducted at group level (e.g. by street, typology).

Where agent-based "what-if" analyses are required, the LDT can use a synthetic population (Synthetic Population – The Decision Lab, z.d.) (virtual households that mirror real distributions) instead of individual records. Data sharing with the municipality and Dorpscoöperatie Aadorp follows WP1/WP5 ethics approvals and consent/anonymisation agreements.

3.2.4 IoT and Real-Time Sensor Data

Live data streams turn the twin from a static model into a **living representation of the PED**. Main streams include:

- **Real-time energy consumption** at building or cluster level, via EMS systems, smart meters or local cooperative/utility/DSO data.
- **Indoor environment and usage data** from pilot locations such as community centre 't Aahoes (e.g. temperature, humidity, CO_2, occupancy, power use).
- **Weather and solar radiation** from KNMI (hourly or higher frequency).

These data typically arrive as CSV or JSON/API feeds with 15-minute or hourly intervals. They are ingested into the LDT/EMS data layer and support:

- monitoring dashboards;
- continuous model validation;
- exploration of dynamic energy labels reflecting actual performance (Beucker et al., 2021; Mazhar et al., 2023) (rather than static EPCs).

Only aggregated or anonymised outputs are exposed in front-end dashboards; raw data remain under the control of data owners with strict access controls.

3.2.5 Energy Infrastructure and Hydrogen Data

Energy-system layers represent the physical backbone needed to evaluate PED scenarios:

- **Electricity networks** (feeders, substations, transformers) and existing gas infrastructure from the DSO (Coteq) and, where needed, TSO (TenneT, GTS).

- **District heating and cooling networks** from municipal ESCOs or other utilities, including existing and planned networks (vector data).

A key innovation in Almelo is the hydrogen micro-network, in which four buildings pilot green hydrogen heating supplied by the H2Hub Twente electrolysis (University of Twente, 2025; Almelo Energie, 2025) facility using renewable electricity. The LDT links hydrogen production, storage and pressure data to the wider energy system, enabling simulation of sector coupling (PV/Wind → H_2 → seasonal heat/power) in line with EU Energy System Integration and Hydrogen Strategy. Sensitive operational details are handled under strict safety and security protocols.

3.2.6 Environmental and Mobility Data

Optional but valuable layers (air quality, noise, urban greening, traffic and EV charging) allow the twin to quantify co-benefits and trade-offs: for example, air-quality gains from phasing out old boilers, peak-load effects of EV charging **(including Vehicle-to-Grid (V2G) options)**, or cooling and health and environmental resilience benefits from additional trees and green space. These data will be very valuable for impact metrics and cross-use case impact trading (e.g., with a CO2e wallet).

- **Mobility and EV charging data**, for example from ElaadNL, municipal systems or private charge point operators (CSV/API time series).

- **Weather and climate normals** from KNMI, supporting long-term resilience analysis.

- **Land use and street network** from OpenStreetMap (OSM, ODbL licence), supporting walkability analysis, parking changes and routing.

These are managed as thematic cloud layers and can be toggled per use case in the Cesium-based dashboards, for example to relate energy measures to local air quality, noise and urban greening benefits.

3.2.7 Data Integration, Anonymisation and Governance

All datasets are brought together in a shared data commons hosted by the Kanaalfront Project Consortium (PED Living Lab). The infrastructure uses cloud-based (or hybrid) storage to maintain:

- **Geospatial, tabular and time-series data** in modular domains (buildings, energy, people, sensors, infrastructure);

- **Common geographic keys** (addresses, coordinates, grid cells) to link datasets.

Open datasets (PDOK/BAG, CBS, KNMI, OSM) are regularly synced, while closed datasets (real-time energy, hydrogen operations, mobility streams, resident inputs) remain under the control of their owners. Access is governed by data-sharing agreements and technical controls.

An anonymisation and privacy-by-design approach is applied to sensitive data:

- Separation of direct identifiers from quasi-identifiers.

- Aggregation and temporal coarsening before external use (e.g. building/block level, hourly/daily summaries).

- Pseudonymisation, with mapping tables stored separately under strict access control.

- Spatial coarsening where needed (e.g. aggregation to 50-100 m grids).
- Application of differential privacy techniques for highly sensitive external aggregates.
- Role-based access control and encryption at rest and in transit.

A Data Protection Impact Assessment (DPIA) has been carried out and all data are shared based on the privacy policy, ensuring compliance with GDPR and the WP1/WP5 ethics framework. All data collection and processing procedures are checked against the project's privacy policy to ensure ethical handling of resident data. (See Deliverable D8.5 for further details on governance).

3.2.8 Data Inventory

A structured data inventory summarises each dataset used in the Almelo LDT, including:

- dataset name and description;
- owner/actor;
- format and data type (vector, raster, time series, 3D geometry);
- source (primary/secondary);
- licence or restrictions;
- personal-data status;
- update frequency.

An example extract is shown in Table 4.

Table 2: Example entries from the Almelo LDT data inventory

No.	Dataset	Data owner / actor	Format / data form	Source	Restrictions & licence	Personal data	Update frequency
1	Building geometry & attributes (BAG)	PDOK - BAG	ESRI Shapefile; vector	Secondary, open data	Open licence, no restrictions	No	Continuous (used yearly)
2	3D building model Kanaalfront	Ad Fontem (architect)	SketchUp / 3D geometry	Primary	Internal project data	No	Irregular (project updates)
3	Energy consumption & labels	CBS	CSV; tabular	Secondary	Open data	No	Yearly
4	Real-time energy consumption	Local cooperative / utility / DSO	CSV/API; time series	Primary	Closed, restricted access	Yes (aggregated/anonymised)	Real-time (15-min)
…	…	…	…		…	…	…

A full version of the inventory is maintained as a living document and acts as the single source of truth for data governance in the pilot.

Taken together, the data architecture combines 3D spatial models, detailed building-energy attributes, social and behavioural inputs, live sensor streams and energy-infrastructure data under a GDPR-compliant, transparent governance framework. The end-to-end workflow-from PDOK/3D BAG via QGIS, Python and FME to 3D CityDB and Cesium-ensures that the Almelo LDT can scale, interoperate and be reused across other 3DxVERSE pilots.

3.3 Models and Simulations

The Almelo-Aadorp LDT transforms raw data into actionable insights through a suite of simulation, behavioural, optimisation and impact models. Developed and refined under WP6 and WP7, these models are calibrated locally and provide a decision-support toolkit for the PED transition.

3.3.1 Energy Balance and Demand Model

Purpose
The core urban energy model estimates the neighbourhood's energy consumption and on-site production at building and district levels, supporting scenario analysis for different technology and retrofit strategies.

Methodology
The model combines:

- building geometry and materials from BAG/3D BAG and architectural models;
- energy labels and historical or real-time consumption profiles (CBS, cooperative/utility data);
- KNMI weather and solar radiation data;
- parameters for district heating (supply temperatures, efficiencies, topology);
- rooftop PV potential and characteristics of storage systems (batteries, thermal buffers).

Using these inputs, it:

- estimates hourly and annual heating, cooling and electricity demand per building;
- computes renewable generation from rooftop PV;
- simulates interventions such as insulation, heat pumps, district heating connections and storage deployment.

Inputs and validation

Model calibration and validation rely on:

- historical and, where available, real-time energy consumption (aggregated and anonymised);

- KNMI weather time series;
- building characteristics from BAG and 3D models;
- performance data from any district heating or similar pilots.

Scenario-based cross-validation compares outputs with performance in comparable neighbourhoods. Sensitivity analyses test robustness with respect to key parameters (insulation quality, occupancy, system efficiencies).

3.3.2 Behavioural and Adoption Model

Purpose
Technical potential alone does not guarantee a successful energy transition. The behavioural model captures how different household types interact with buildings, technologies and incentives, and how they adopt measures over time.

Methodology
Using a synthetic population and/or aggregated household segments, the model represents:

- heating/cooling preferences;
- appliance and EV charging patterns;
- responses to measures, tariffs and subsidies;
- social influence and information diffusion (e.g. neighbours, local ambassadors, co-design workshops).

Agent-based or rule-based mechanisms simulate how adoption spreads and how participation barriers (cost, awareness, digital skills, technology preferences) affect uptake.

Inputs and validation

- Aggregated socio-demographic data and household segments.
- Survey data and co-design feedback from Kanaalfront sessions.
- Observed participation rates from local programmes (insulation, PV, heat pumps).

The model supports inclusive engagement strategies by revealing where additional support is needed (e.g. for low-income or low-digital-literacy groups) and by informing design of incentives and communication.

3.3.3 Optimisation Model (Decision Support)

Purpose
The optimisation engine explores combinations of measures and system configurations that best meet PED objectives under technical, financial and social constraints.

Methodology
Using outputs from the energy and behavioural models, a (multi-)objective optimisation (e.g. linear programming or evolutionary algorithms) searches for solutions that:

- minimise CO_2 emissions and energy costs;
- maximise local renewable self-consumption and thermal comfort;
- respect constraints such as grid capacity, district heating limits, budget envelopes and acceptable disruption for residents.

Inputs include demand and generation profiles, storage capacities, tariffs, CAPEX/OPEX, subsidies and network constraints.

Validation

- Comparison of optimised scenarios with historically successful configurations in similar projects.
- Stress-testing under alternative assumptions (higher energy prices, reduced subsidy levels).
- Expert and stakeholder review to ensure solutions are plausible and socially acceptable.

Results are fed into the LDT as scenario layers and form part of the evidence base for D8.2 and D8.4.

3.3.4 “What-If” Interactive Scenario Simulator

Purpose

The interactive simulator allows planners and residents to explore “what-if” scenarios in a simple, intuitive way without needing expert modelling skills.

Citizen interaction

Users access a web-based interface integrated with the LDT and can adjust parameters such as:

- heating system type (e.g. gas boiler, all-electric heat pump, hydrogen-ready hybrid);
- insulation or retrofit depth;
- rooftop solar coverage;
- basic EV charging behaviour;
- optional greening measures (e.g. trees, green roofs, if linked to microclimate modules).

Results presentation

The interface provides immediate, easy-to-understand feedback:

- estimated CO_2 savings and changes in energy costs;
- shifts in renewable self-consumption and grid import/export;
- simple scores or traffic-light indicators for comfort, resilience and affordability;
- maps and heatmaps showing changes in energy performance.

Trade-offs between configurations (e.g. “Max Solar + District Heating” vs. “Hydrogen Hybrid”) are visualised through side-by-side comparisons and charts. The simulator builds on the ESDL-based system descriptions, ESSIM-style dashboards and ArcGIS/Cesium visualisations prototyped in WP6/WP7.

3.3.5 Dynamic Building Performance Model

Purpose

At building level, the twin integrates sensor-driven models for key assets (e.g. community centre ’t Aahoes) to demonstrate live building energy management (BEMS) capabilities.

Functionality

- Continuous monitoring of indoor conditions (temperature, humidity, CO_2), HVAC operation, occupancy and power consumption.
- Anomaly detection (e.g. malfunctioning equipment, unexpected baseload).
- Predictive control strategies (e.g. pre-heating before events, demand response).
- Near-real-time updates of performance indicators and “dynamic energy labels”.

These high-resolution measurements are used to validate the energy model at building scale and showcase how AI-based predictive modelling can optimise comfort and efficiency while keeping physical and digital assets synchronised.

3.3.6 Environmental Impact and Co-benefit Models

Purpose

To link energy scenarios to broader sustainability outcomes, simplified impact models compute CO_2 emissions, air pollutants, peak-load changes and resilience indicators.

Methodology

- Use emission factors (e.g. CO_2 per kWh or m^3 gas) to estimate territorial CO_2e reductions from heating and electricity.
- Where data permit, extend to NOx and particulate matter, especially in scenarios that phase out fossil boilers or reduce traffic.
- Combine energy and mobility data to analyse effects of EV adoption, charging strategies and modal shifts.
- Relate changes in greening (trees, green roofs) to urban heat and comfort indicators.

Validation includes comparison with municipal or national emission inventories and, where applicable, performance data from the hydrogen pilot once operational.

3.3.7 Summary of Analytical Toolkit

Together, these models address the technical, behavioural and environmental dimensions of the energy transition. By combining calibrated simulations, social adoption modelling, AI-based optimisation, intuitive “what-if” tools and real-time feedback loops, the Almelo LDT provides a transparent, interoperable and participatory decision-support system that directly operationalises the objectives of D8.1.

3.4 Platform Architecture and User Interfaces

The Almelo-Aadorp LDT is delivered through a modular platform architecture that integrates the data and models described above into practical tools for planners, engineers, community partners and residents. A core design principle is cross-platform interoperability, demonstrating that the same datasets and models can operate in both ESRI and open-source environments.

3.4.1 Technology Stack and Interoperability

The technical stack follows a dual-platform approach:

- **ESRI platform (ArcGIS Pro, ArcGIS Urban, ArcGIS Online, StoryMaps)**
  - Used for rapid GIS analysis, planning workflows and rich communication products.
  - Hosts current Aadorp prototypes and integrates with WP7 testbeds.
- **Open platform (CesiumJS + Cesium Ion)**
  - Serves as the primary web-based 3D environment for the Kanaalfront PED twin.
  - Supports standard formats (3D Tiles, CityJSON, GeoJSON, raster/terrain tiles) for scalable, browser-based visualisation.

Back-end services run on a cloud spatial database (e.g. PostgreSQL/PostGIS), exposing data via REST/OGC APIs. Model services pull inputs through APIs and write results back as scenario layers that can be consumed by both ESRI and Cesium front ends.

Deployment follows DevOps/container principles and adheres to OASC Minimal Interoperability Mechanisms (MIMs), enabling interoperability with national platforms and the EU LDT Toolbox. Cesium acts as an “open-by-design” 3D backbone for digital twins (Noon, 2025).

3.4.2 Planner Dashboard and 3D Expert Interface

For planners and technical experts, the LDT is accessed through a secure web dashboard offering:

- An interactive 2D/3D map with advanced layer controls (LOD2 buildings, energy labels, PV potential, district heating, hydrogen, electricity and gas networks).
- Live KPI panels and time-series charts for data such as indoor climate and energy use at ’t Aahoes.
- Form-based “what-if” tools for simulating retrofit and system scenarios, with outputs on CO_2, demand and costs.
- Export functions (PDF, Excel, GeoJSON) for reporting, internal analysis and packaging content for the EU LDT Toolbox.

- Experimental AR/VR capabilities for on-site visualisation in workshops.

Access is role-based, ensuring that only authorised staff can view or edit sensitive layers.

3.4.3 Public Engagement Portal

For residents and other non-expert users, a public engagement portal combines Cesium-based 3D maps with StoryMap-style narratives. Main features include:

- **Community dashboard** with high-level indicators on renewable share, PED targets and progress.
- **Simplified map** showing basic building profiles and example retrofit packages.
- **Public "what-if" simulator** with reduced parameter sets and easily understandable outputs (e.g. CO_2 colour scales, approximate cost ranges).
- **Educational and participation pages** explaining hydrogen, district heating, all-electric options and the role of digital twins, with embedded surveys and idea boards.
- A design that is **Dutch-first and accessibility-conscious**, complemented by offline outreach as required by the ethics framework.

3.4.4 Data Security and System Management

All API traffic is encrypted (HTTPS), and access to back-end services is managed through role-based access control. DevSecOps pipelines (staging → security tests → production) support secure updates, with:

- audit logs for data imports, configuration changes and user actions;
- regular backups and resilience measures;
- strict separation between test and production environments.

Only anonymised or aggregated data are exposed on public interfaces, and personal data processing is governed by DPIA outcomes and GDPR requirements. Outputs and KPIs can be packaged via open APIs for publication in the EU LDT Toolbox or other dashboards.

3.5 Interoperability, Trust and Data Governance

Interoperability, trust and governance are embedded across the Almelo LDT. For a comprehensive description of the project-wide interoperability and data governance frameworks, please refer to Deliverable D8.5 (Interoperability and Data Governance). The following sections outline how these frameworks are operationalised specifically for the Almelo pilot to ensure it functions as an open, interoperable node within the wider 3DxVERSE and EU ecosystems.

3.5.1 LDT Platform and External Data Interfaces

The core platform is an ArcGIS-based LDT with extensive geospatial/IoT standards support, complemented by the open Cesium environment. Key elements include:

- Ability to read/write Shapefile, GML/CityGML, KML and consume OGC WMS/WMTS/WFS services.
- Integration with municipal GIS layers via open services, enabling easy exchange with tools such as QGIS.
- An Energy System Description Language (ESDL) layer providing a common, machine-readable representation of energy assets and time series.
- An NGSI-LD context broker to ingest and expose IoT data (smart meters, sensors) with semantic context.
- Connectors to building automation and IoT protocols (BACnet/IP, MQTT, LoRaWAN), with normalisation to the context layer.

3.5.2 Syntactic and Semantic Interoperability

Syntactic interoperability is ensured via open formats and APIs (OGC APIs, JSON/GeoJSON, NGSI-LD, CSV, REST/HTTP, MQTT).

Semantic interoperability is ensured by:

- ESDL for energy systems (standardised concepts such as EnergyAsset, PowerCapacity, EnergyCarrier).
- SAREF and SAREF4ENER/SAREF4BLDG for IoT and building semantics.
- FIWARE Smart Data Models and mappings to IEC CIM for power systems where relevant.
- Use of JSON-LD contexts so that terms such as *Temperature* or *Power* have consistent meaning across systems.

Compliance with OASC MIMs is checked via the interoperability testbed, ensuring readiness to interoperate with other MIM-aligned cities and platforms.

3.5.3 Alignment with System-of-Systems Goals and EU Frameworks

The Almelo LDT implements the LDT Reference Architecture (D3.1) and aligns with ESRI's WP7 reference implementation, ensuring consistent building blocks (ingestion, common services, data-space links) across pilots. It also considers broader European frameworks:

- INSPIRE-compliant APIs for public-sector geospatial data sharing.
- The European Interoperability Framework (EIF) and EIRA for organisational/legal interoperability with government services.
- Where relevant, oneM2M and other IoT standards to support future integration.

Through open APIs and documented mappings, the Almelo LDT contributes to a reusable "digital commons" of assets (models, schemas, adapters) for other cities.

3.5.4 Tools, Standards and Protocols

The platform relies on:

- Software and security practices aligned with ISO 27001, DevSecOps, GDPR and accessibility standards.

- Geospatial metadata based on ISO 19115/19119.

- APIs and protocols such as REST/JSON/JSON-LD, NGSI-LD, OGC API Features/Tiles, MQTT and BACnet/IP (via gateways).

- Data models and ontologies including ESDL, SAREF, FIWARE Smart Data Models, IEC CIM, CityGML and 3D Tiles/I3S.

A knowledge-graph approach is used to link IoT sensors (SAREF) with buildings (CityGML) and energy simulations (ESDL), supporting the 3DxVERSE system-of-systems ontology vision.

3.5.5 Conclusion: A Reusable Interoperable Blueprint

By combining open geospatial stacks, ESDL-based energy semantics, NGSI-LD context management, SAREF/FIWARE ontologies and robust governance frameworks, the Almelo LDT operationalises interoperability and trust-by-design from devices to dashboards. Conformance via interoperability testing and application of DevSecOps/GDPR/ISO 27001 practices makes the twin future-proof and vendor-neutral.

As such, the Almelo-Aadorp LDT serves as a replicable blueprint for federated Positive Energy District twins across Europe, fully consistent with 3DxVERSE’s system-of-systems philosophy and the goals of D3.1, D4.1 and D5.1.

4. PILOT IMPLEMENTATION STRATEGY

The implementation of the Almelo-Aadorp Local Digital Twin (LDT) follows a phased and collaborative deployment model. It combines technical development, data integration, citizen engagement and evaluation preparation into a coherent set of workstreams. This chapter describes how the objectives of D8.1 are operationalised in practice, how implementation is staged over time and how the pilot is embedded in the broader 3DxVERSE lifecycle.

4.1 Implementation Objectives and Workstreams

The implementation strategy for Almelo-Aadorp is organised into seven interlinked workstreams (WS). Together, they translate the high-level objectives of D8.1 into concrete tasks and outputs.

4.1.1 WS1 - Implement and Validate the Almelo-Aadorp Local Digital Twin

This workstream focuses on deploying a functioning Local Digital Twin for the Aadorp Positive Energy District (PED):

- Deploy and document the PED Digital Twin, integrating:
    - 3D building and terrain models;
    - building energy and demographic attributes;
    - energy infrastructure layers (electricity, gas, district heating, hydrogen micro-network).
- Ensure that the LDT represents real-world infrastructure and transition options, including:
    - the district heating concept and alternative heat scenarios;
    - the hydrogen H_2 hub route connecting the initial four pilot addresses;
    - rooftop PV deployment;
    - wind turbine deployment;
    - storage options;
    - the Kanaalfront redevelopment area and planned new-build.
- Validate an initial minimum viable product (MVP) configuration of the twin that can be used in planning and engagement sessions.

4.1.2 WS2 - Demonstrate Interoperability Across Testbeds and Platforms

This workstream demonstrates cross-platform operation and openness of the Almelo LDT:

- Integrate the Almelo datasets and models into both:
    - the ESRI Local Digital Twin Testbed;

  - the Open Digital Twin Testbed (Geonovum / Netherlands3D on Cesium).

- Test and document interoperability mechanisms for:
  - data exchange (e.g. ESDL → ArcGIS → ESSIM → Hub);
  - model portability (scenario definitions, KPIs);
  - visualisation in both proprietary and open-source environments.
- Provide pilot outputs (ESDL models, scenarios, dashboards) in a form suitable for contribution to the EU Local Digital Twin Toolbox and CitiVerse-related activities.

4.1.3 WS3 - Operationalise Trust, Security and Data-Governance Frameworks

This workstream ensures that privacy, security and governance principles are embedded in the pilot from the outset:

- Apply the 3DxVERSE Trust Framework and DevSecOps principles to the Almelo LDT, including:
  - secure development, testing and deployment pipelines;
  - encrypted communication and role-based access control.
- Conduct and maintain a Data Protection Impact Assessment (DPIA) and, where necessary, other PIA/ethics documentation, in line with WP1, WP5 and the **ENISA Risk Management Framework..**
- Define a data-governance model for the pilot covering:
  - open-data policies and dataset licensing;
  - consent and anonymisation procedures for citizen inputs and smart-meter/IoT data;
  - audit logs for data usage and energy simulations.
- Explore (where feasible within the pilot scope) the use of Decentralised Identifiers (DIDs) and Verifiable Credentials (VCs) for secure and verifiable interactions between residents, municipal systems and operators (Web-based Digital Twins for Smart Cities Interest Group Charter, z.d.).

4.1.4 WS4 - Develop and Calibrate Simulation and Decision-Support Models

This workstream focuses on the analytical backbone of the twin:

- Implement the initial suite of models for the Almelo-Aadorp PED, including:
  - urban energy supply and demand balance models;
  - behavioural and adoption models;

  - optimisation models for PED configuration;
  - environmental and co-benefit models (CO_2, air quality, resilience).
- Calibrate these models using:
  - building and energy data (BAG, CBS, PBL Startanalyse 2025, municipal programmes);
  - measured data from pilot locations (e.g. ’t Aahoes, hydrogen pilot, PV systems);
  - survey and co-design data from residents.
- Integrate model outputs into maps, dashboards and “what-if” tools for planners and citizens, ensuring that the decision-support interface is understandable and actionable.

4.1.5 WS5 - Prepare Evaluation through KPI Framework and Monitoring

This workstream prepares the ground for D8.2 (evaluation) by operationalising KPIs and monitoring methods:

- Apply the consolidated 3DxVERSE KPI framework to the Almelo pilot, covering five KPI families:
  - Societal participation;
  - Sustainability;
  - Trust & ethics;
  - Interoperability;
  - Economic value.
- Define data pipelines to populate KPIs at three stages:
  - pre-pilot baseline;
  - mid-pilot operation;
  - post-pilot outcomes.
- Align KPIs with national and municipal targets (e.g. CO_2 reduction, energy labels, inclusion indicators) and ensure comparability with other 3DxVERSE pilots (Hamburg, Oranjestad, Timișoara).
- Link KPI monitoring to the RAID log, so that risks and assumptions are ssystematically tracked against observed performance **and compliant with the ENISA Risk Management Framework.**

4.1.6 WS6 - Engage Citizens and Stakeholders

This workstream embeds citizen participation and multi-actor collaboration into implementation:

- Co-design and execute a multi-channel engagement plan (workshops, Senses walks, Citizen Fora, online portal, newsletters), drawing on the New European Bauhaus (NEB) Toolbox components (see D5.1 and D8.5 for social design details).
- Use the LDT and its interfaces in engagement activities, for example by:
    - visualising “before/after” energy scenarios;
    - allowing residents to test simple retrofit and heating options;
    - presenting trade-offs between different planning choices.
- Make the Almelo LDT accessible at different levels of complexity (expert vs. citizen), with specific attention to:
    - elderly residents;
    - tenants and low-income households;
    - residents with low digital literacy.
- Document qualitative feedback on usability, trust and perceived value of the twin, feeding it into iterative improvements and the evaluation framework.

4.1.7 WS7 - Capture Lessons and Recommendations for Replication and Scaling

Finally, this workstream ensures that Almelo-Aadorp contributes to learning and scaling across 3DxVERSE and beyond:

- Systematically record lessons learned on governance, collaboration, data standards, technical integration and citizen engagement during implementation.
- Identify reusable artefacts (data models, code modules, engagement formats, guidance documents) that can be shared with other pilots and cities.
- Formulate recommendations for:
    - scaling the Almelo LDT to more districts in Almelo;
    - replication in other Dutch or European municipalities pursuing PEDs;
    - contributions to EU-level toolboxes and guidance on Local Digital Twins.

4.2 Phased Implementation Plan

The workstreams described above are delivered through a phased approach that aligns technical readiness, stakeholder engagement and evaluation needs.

4.2.1 Phase 1 - Infrastructure and Baseline Setup

In Phase 1, the focus is on establishing a robust technical and data foundation and aligning key stakeholders:

- Build the initial 3D twin using authoritative Dutch datasets such as BAG (building/address registry) and AHN (national elevation model), ensuring reliable building footprints, heights and terrain (Alles Over de BAG - Kadaster.nl Zakelijk, 2025).
- Populate baseline modules for:
  - building energy labels and consumption;
  - demographics and social context;
  - key mobility and environmental indicators, where available.
- Develop an ESDL-based representation of local energy assets and connections to support model portability across tools and testbeds (ESDL Documentation | ESDL, z.d.).
- Install and connect IoT sensors at pilot locations (e.g. ’t Aahoes) for indoor environment and energy monitoring, and prepare ingestion of consent-based smart-meter data streams (EU LDT Toolbox, 2025).
- Conduct initial co-design sessions with the municipality, Dorpscoöperatie Aadorp, Almelo Energie and other core partners to define requirements, ethical safeguards and use-case priorities (Leerling et al., 2023).

The outcome of Phase 1 is a minimum viable Local Digital Twin for Aadorp, with baseline 3D visualisation, key datasets integrated and data pipelines in place to support pilots from 2026 onwards (The LDT CitiVERSE EDIC Is A Fact!, 2024).

4.2.2 Phase 2 - Pilot Execution and Scenario Testing

In Phase 2, the focus shifts to active pilot deployment and scenario exploration:

- Implement the hydrogen micro-pilot, connecting the initial group of four Aadorp buildings to locally produced green hydrogen (H2Hub Twente) in cooperation with partners such as UTwente, Cogas and Solenco, as part of broader IS2H4C activities (Van Den Heuvel, z.d.).
- Support Kanaalfront co-design by running participatory workshops where residents and planners explore spatial and energy options in the twin, consistent with municipal Kanaalfront exploration documents.
- Expand data ingestion to include:

  - (consented) smart-meter telemetry;
  - PV generation;
  - building automation outputs. This improves calibration and enables more detailed KPI reporting, following microgrid best practice (demand-generation-reliability coupling) (García Vera et al., 2019).
- Launch a public-facing dashboard and portal (e.g. via ArcGIS Hub and/or Cesium-based front-ends) to communicate indicators, gather feedback and enhance trust. (Introduction To ArcGIS Hub-ArcGIS Hub | Documentation, z.d)
- Extend system functionality via ESDL-based energy system modelling, additional scenario types and KPI dashboards, ensuring that simulations are portable between proprietary and open environments (ESDL Documentation | ESDL, z.d).

By the end of Phase 2, the Almelo LDT is used in real decision processes, both for planning (e.g. zoning, investment prioritisation) and for engagement with residents.

4.2.3 Phase 3 - Iterative Calibration and Monitoring

Phase 3 focuses on continuous improvement, validation and preparation for evaluation:

- Monitor seasonal effects (winter heating, summer PV) and validate simulations against measured data:
  - hydrogen consumption and system operation (Bouwmeester, 2024);
  - electricity and heat loads;
  - indoor comfort and environmental indicators.
- Refine LDT models using real-world validation data, applying multi-objective evaluation (reliability, cost, emissions) and updating parameters where necessary (García Vera et al., 2019).
- Keep engagement channels active through ongoing workshops, surveys and portal-based feedback; use this input to refine user interfaces and communication (Introduction To ArcGIS Hub-ArcGIS Hub | Documentation, z.d).
- Use the twin to support operational planning (e.g. phasing of retrofits, targeting subsidy schemes, assessing network constraints) (Discover EU LDT Toolbox, z.d.).
- Consolidate evidence, KPIs and lessons learned into inputs for D8.2 (evaluation) and D8.4 (replication), and prepare contributions for EU-level dissemination (e.g. LDT Toolbox, CitiVerse outputs).

The outcome of Phase 3 is a validated, citizen-centred LDT that can either continue in regular use within Almelo or be further scaled and replicated, supporting European ambitions for PEDs and Local Digital Twins (The LDT CitiVERSE EDIC Is A Fact!, 2024).

4.3 Roles, Dependencies and Risk Considerations

The pilot is implemented within the broader 3DxVERSE project management and risk framework, including the RAID log maintained under WP2.

Key roles and responsibilities are defined in Chapter 2 and can be summarised as follows:

- The Municipality of Almelo is accountable for spatial planning decisions, public goals and integration of the LDT in municipal processes.
- The Dorpscoöperatie Aadorp is the key community partner, ensuring resident interests are represented and engagement is meaningful.
- Technical partners (TNO, UT, Saxion, IT providers) are responsible for LDT development, data integration and modelling.
- Utilities and infrastructure operators (Cogas, Coteq, H2Hub Twente, water and environmental agencies) ensure that real-world infrastructure constraints and safety requirements are correctly reflected in the twin and pilots.

Major dependencies and risks for implementation include:

- Data availability and quality: delays or gaps in access to smart-meter, PV, or infrastructure data could constrain model accuracy and KPI monitoring.
- Regulatory approvals: permits for hydrogen pilots, construction works or data sharing may delay or limit the scope of certain use cases.
- Technical integration challenges: aligning different platforms, standards and ontologies may require additional development effort and could impact timelines.
- Stakeholder capacity and continuity: changes in staff, political priorities or community engagement capacity could influence the pace and depth of pilot activities.

Mitigation measures are tracked in the RAID log and include early engagement with regulators, clear data-sharing agreements, modular technical design and continuous communication with political and community stakeholders.

4.4 Link to Future Deliverables (D8.2)

Deliverable D8.1 lays the implementation foundation for the Almelo-Aadorp pilot. The subsequent WP8 deliverables build directly on the work described in this chapter:

- **Pilot Evaluation** will use the implemented LDT, calibrated models and KPI framework to assess the technical, social and governance performance of the Almelo pilot. Evidence generated during Phases 2 and 3 (measurements, engagement feedback, decision logs) will form the core input to this evaluation.
- **Replication and Scaling** will draw on the lessons, reusable artefacts and recommendations captured in WS7. It will identify how Almelo's approach can be adapted to other

neighbourhoods, municipalities and countries, and how it can contribute to European guidance and toolboxes for Local Digital Twins and Positive Energy Districts.

Through this staged approach, D8.1 not only delivers a working Local Digital Twin for Almelo-Aadorp but also sets up a structured learning and scaling pathway within 3DxVERSE and the wider European digital-twin ecosystem.

5. EVALUATION FRAMEWORK AND KPIS

The Almelo-Aadorp pilot is not only an implementation project but mostly a learning and evidence-generation exercise. This chapter explains how the Local Digital Twin (LDT) and the Positive Energy District (PED) are evaluated, which Key Performance Indicators (KPIs) are used, and how data are collected and compared across time and between 3DxVERSE pilot sites.

5.1 Evaluation Objectives and Scope

The evaluation of the Almelo-Aadorp pilot has a dual focus:

1. **Technical performance**
    - Does the PED LDT deliver measurable improvements in energy efficiency, CO_2 reduction, renewable share and interoperability?
    - Are the models and data pipelines accurate, robust and usable in real decision processes?
2. **Social impact and engagement**
    - Does the LDT support meaningful citizen participation and inclusive governance?
    - Does the pilot contribute to quality of life, trust in digital tools and perceived fairness of the transition?

The evaluation framework is aligned with the 3DxVERSE KPI framework defined in WP6, ensuring that results from Almelo can be compared with those from other pilots (Hamburg, Oranjestad, Timișoara). It spans three stages:

- **Pre-pilot baseline** - conditions before LDT and PED interventions;
- **Mid-pilot operation** - intermediate status during active pilots;
- **Post-pilot outcome** - situation at the end of the project period.

The Almelo LDT itself is an evaluation instrument: it provides calibrated models, monitoring dashboards and decision logs that document how evidence is used in planning and governance.

5.2 KPI Framework for the Almelo Pilot

The KPI framework reflects the **dual mission** of the Almelo-Aadorp pilot:

- **Technical and environmental performance**:
    - energy consumption and efficiency;
    - CO_2 reduction and renewable share;
    - interoperability and reuse of data and models.
- **Social and governance performance**:
    - depth and breadth of citizen participation;
    - inclusion of vulnerable groups;
    - perceived quality of life and well-being;
    - extent to which the digital twin informs real decisions.

To ensure consistency within 3DxVERSE, Almelo’s KPIs are grouped into two main clusters:

1. **Citizen Engagement & Inclusion**: indicators that capture how residents and stakeholders are involved and how this affects social outcomes.
2. **Positive Energy District (Technical Performance)**: indicators that capture energy, CO_2 and interoperability performance of the PED and LDT.

These are underpinned by common KPI families agreed in WP6:

- Societal Participation;
- Sustainability;
- Trust & Ethics;
- Interoperability;
- Economic Value.

5.3 KPI Matrix

5.3.1 Citizen Engagement & Inclusion KPIs

These KPIs measure how the Almelo LDT supports participation, inclusion and perceived benefits.

Table 3: Citizen Engagement & Inclusion KPIs

#	KPI	What it measures	Data sources	Timing	Cross-pilot relevance
1	Increased Citizen Participation	Breadth of involvement - number and diversity of residents participating in twin-enabled workshops, dialogues and events.	Attendance logs; short demographic questionnaires at events.	Baseline (existing participation) → per event → post-pilot aggregate.	Comparable to engagement metrics in other pilots; indicates reach of LDT-based engagement.
2	Level of Participation (Feedback Activity)	Depth of engagement - contributions per participant and the degree to which feedback is integrated into plans.	Digital platform analytics (comments, scenario interactions); review of planning documents and decision minutes.	During pilot; final assessment at project end.	Mirrors feedback-integration metrics across all 3DxVERSE sites.
3	Social Inclusion in Planning	Inclusiveness of participation for groups such as elderly, low-income, tenants and low-digital-literacy residents.	Demographic breakdowns of participants; input from local organisations; accessibility and usage analytics for the portal.	Continuous tracking; pre/post comparison of representation.	Aligns with EU digital inclusion indicators and inclusion KPIs in other pilots.
4	Improved Quality of Life & Well-Being	Perceived social and comfort outcomes (well-being, comfort,	Pre/post surveys and interviews; standardised well-being indices or	Baseline → mid-pilot check → post-pilot survey.	Complements technical KPIs by linking PED outcomes to

		satisfaction, sense of empowerment).	scales where applicable.		human-centric benefits.
5	Decisions Influenced by the Digital Twin	Extent to which municipal or cooperative decisions explicitly use LDT insights and citizen input.	Municipal records; meeting minutes; decision logs referencing LDT outputs.	Tracked throughout implementation; consolidated at project end.	Comparable with decision-support KPIs for other digital twin domains (e.g. mobility, logistics).
6	Reduction of Consumption-Based Emissions	Behaviour-driven CO_2e reduction (e.g. from mobility, home energy behaviour, diet/waste) attributed to LDT-enabled awareness and actions.	Pre/post surveys; aggregated energy/mobility data; outputs from behavioural/agent-based models.	Baseline → post-pilot quantification.	Connects behaviour change across different thematic pilots (travel, living) within 3DxVERSE.

5.3.2 Positive Energy District Technical KPIs

These KPIs capture how far Almelo-Aadorp progresses toward PED status and interoperable LDT maturity.

Table 4: Positive Energy District Technical Performance KPIs

#	KPI	What it measures	Data sources	Timing	Cross-pilot relevance
7	Energy Consumption Efficiency	% reduction in total energy use and peak demand for the pilot area compared to baseline.	Smart-meter logs (aggregated); BEMS records; grid-load data from DSO.	Baseline year vs. pilot years; seasonal like-for-like comparisons.	Benchmarked with efficiency outcomes in other PED/sustainable-living pilots.
8	Local Renewable Energy Share	Share of district demand supplied by local renewable sources (PV, local heat, etc.).	Generation meters; inverter data; district consumption data.	Baseline (if any local RES) vs. post-pilot; annual aggregates.	Key PED indicator enabling cross-site comparison of renewable integration.
9	Reduction in CO_2 Emissions (Energy)	Territorial CO_2e reduction from changes in heating and electricity consumption.	Energy consumption records + emission factors; district heating and hydrogen performance data.	Annual baseline vs. post-pilot, with interim trends.	Universal KPI for climate reporting across all 3DxVERSE pilots.
10	Digital Twin Integration (Data Sources)	Degree of interoperability and data richness - number and diversity of connected datasets (IoT,	Integration registry; classification of data sources by type and domain.	Continuous tracking; final snapshot at project end.	Standard digital twin maturity KPI across pilots (extent of integrated domains).

		GIS, ESDL, social, infrastructure).			
11	Replicability & Scalability	Extent to which Almelo solutions are reusable and adopted elsewhere (components, APIs, methods).	Documentation review; records of reuse by other cities/pilots; contributions to EU LDT Toolbox.	Mainly end-of-project; updated in D8.4 and follow-up.	Directly measures the contribution of Almelo to 3DxVERSE scaling and EU-level assets.

5.4 Evaluation Methodology and Data Collection

The KPIs above are supported by a mixed-methods evaluation methodology that combines quantitative monitoring with qualitative insights.

5.4.1 Technical Performance Validation

For technical performance, the evaluation focuses on model-to-reality checks and system-level effects:

- **Model validation**
  - Compare simulated energy demand, peak loads and emissions reductions against measured data from smart meters, BEMS and the hydrogen pilot.
  - Use seasonal periods (e.g. winter heating, summer PV) to check how well models capture real behaviour under different conditions.
- **Use-case specific KPIs**
  - For the PED: annual CO_2 reduction and changes in peak electricity demand (as a proxy for grid reliability and flexibility).
  - For Kanaalfront redevelopment: improvements in building performance (e.g. heating demand per m^2 after retrofits), renewable share and infrastructure utilisation.
- **Multi-criteria lens**
  - Evaluate scenarios and implemented measures through a threefold lens: reliability, cost-effectiveness and environmental gains.
  - Treat reduced peak load via demand response and storage as an improvement in reliability/resilience, consistent with microgrid evaluation practice.
- **AI-enhanced forecasting**
  - Where applied, machine-learning models are used to refine demand forecasts and scenario outputs (Rella, 2024).
  - Forecast accuracy is checked with back-testing against historical time series.
- **Benchmarking and cross-site comparison**

- Quantitative results for Almelo are compared to baseline conditions and, where meaningful, to similar neighbourhoods or pilot sites (Hamburg, Oranjestad, Timișoara).

The technical evaluation uses outputs from the models described in Chapter 3, together with LDT dashboards and logs, to ensure traceability between data, models and reported KPIs.

5.4.2 Social Impact and Engagement Assessment

For social impact, the evaluation emphasises **citizen-centric and participatory methods**:

- **Quantitative engagement KPIs**
    - Track the number and diversity of participants in events and online platforms.
    - Collect frequency and type of interactions with the public portal and “what-if” tools.
- **Qualitative feedback**
    - Conduct interviews, focus groups and surveys with planners, Dorpscoöperatie representatives, residents and other stakeholders.
    - Assess perceived usability, trust, clarity and value of the twin:
        - Are 3D maps and dashboards understandable?
        - Do residents feel their input influences decisions?
        - Does the twin increase trust in local institutions and the transition process?
- **Inclusion and accessibility checks**
    - Monitor whether vulnerable and underrepresented groups (tenants, low-income households, elderly, low-digital-literacy groups) are adequately reached.
    - Adjust engagement methods (e.g. more offline or low-tech formats) if gaps are identified.
- **Citizen-as-analyst approach**
    - In some workshops, residents are invited to explore LDT outputs themselves and interpret findings, reinforcing their role as active analysts, not only data providers (Adade & de Vries, 2025).

Findings from these activities are coded and synthesised, then linked back to the engagement and inclusion KPIs (1-6).

5.4.3 Monitoring Timeline and Cross-Pilot Comparison

The evaluation follows a timeline-based monitoring approach:

- Baseline (pre-pilot)
    - Collect historical data on energy use, emissions and participation.
    - Conduct initial resident surveys and map existing engagement channels.
- During pilot (mid-pilot)
    - Continuously monitor technical KPIs (energy, CO_2, data integration).
    - Regularly track engagement metrics and collect interim feedback on the LDT interfaces.

  - Feed issues and opportunities into the RAID log and implementation adjustments.

- Post-pilot (end-of-project)
  - Perform a comprehensive KPI assessment and compare with baseline.
  - Consolidate lessons learned and recommendations for replication.

For cross-pilot comparison, common KPIs such as CO_2 reduction, renewable share, data integration and replicability are aligned with the WP6 framework. Site-specific indicators (e.g. particular forms of citizen engagement or local governance innovations) are documented as qualitative case evidence, providing richer context for cross-site learning.

Overall, the evaluation framework ensures that the Almelo-Aadorp LDT is assessed not only as a technical system, but as an instrument for inclusive governance and just energy transition, generating actionable evidence for future deployment in Almelo and replication across Europe.

6. CONCLUSIONS AND REPLICATION PATHWAY

6.1 Key Contributions of D8.1

Deliverable D8.1 has established the first full implementation phase of the Almelo-Aadorp Local Digital Twin (LDT) as a reference for sustainable living communities and Positive Energy Districts (PEDs) within 3DxVERSE as follows:

- Defined the local context, governance model and stakeholder ecosystem for the Almelo-Aadorp pilot, centred on the Kanaalfront redevelopment and co-governance between the Municipality of Almelo and Dorpscoöperatie Aadorp.
- Designed and implemented a standards-based LDT architecture that integrates 3D spatial models, building-energy attributes, socio-demographic data, IoT streams and energy infrastructures (including a hydrogen micro-network), under a GDPR-compliant data-commons governance model.
- Developed a suite of analytical models-energy balance, behavioural adoption, optimisation, building performance and environmental impact-forming a coherent decision-support toolkit for the PED transition.
- Deployed a dual-platform implementation (ESRI and open Cesium-based stack), demonstrating interoperable operation across proprietary and open environments and aligning with OASC MIMs and EU Local Digital Twin ambitions.
- Embedded trust, security and data-governance frameworks into the pilot, including DPIA-based privacy-by-design measures, role-based access control, DevSecOps practices and semantic interoperability based on ESDL, NGSI-LD, SAREF and related standards.
- Prepared a phased implementation strategy (baseline setup, pilot execution and scenario testing, iterative calibration and monitoring) with clearly defined workstreams and responsibilities.
- Established an evaluation framework and KPI matrix that covers both technical/PED performance and citizen engagement and inclusion, aligned with the 3DxVERSE KPI framework and ready to be used in D8.2.

Taken together, these contributions show how a Local Digital Twin can move from concept and prototype (D6.1, D7.1) to a functioning, governed and citizen-oriented implementation that supports the energy transition at neighbourhood scale.

6.2 Lessons Learned and Recommendations for Scaling

The implementation planning and architecture work for Almelo-Aadorp yields several preliminary lessons that are relevant for future scaling and replication:

1. **Governance and co-ownership matter as much as technology**
   A clear governance model-anchored in the partnership between the municipality and Dorpscoöperatie Aadorp, with transparent roles for utilities, housing associations and knowledge partners-is essential to ensure that the LDT is trusted, used and maintained. Replication efforts should start by clarifying governance and co-ownership before designing the technical stack.

2. **Open standards and dual-stack deployments reduce lock-in and increase reuse**

   Using CityGML/CityJSON, ESDL, NGSI-LD, SAREF and OASC MIMs, and operating both ESRI and open (Cesium) front-ends, has shown that Local Digital Twins can be both practical and open. Cities aiming to build on Almelo's approach are encouraged to adopt a similar standards-first, dual-stack mindset to safeguard future interoperability and data-space integration.

3. **Data governance and privacy-by-design are enabling conditions, not afterthoughts**
   The Almelo experience confirms that addressing GDPR, DPIA, consent and anonymisation from the start builds trust and avoids later bottlenecks in data access. A clear data inventory, classification and governance model should be treated as a core pillar of any LDT-based PED pilot.

4. **Socio-technical integration improves relevance and legitimacy**
   Combining technical models with behavioural and social data (synthetic populations, co-design inputs) ensures that scenarios are not purely techno-economic but reflect real adoption patterns, barriers and equity considerations. Replication should invest in similar behavioural and inclusion modelling, especially where energy poverty or vulnerable groups are present.

5. **Citizen-facing tools must be deliberately simplified and tested**
   The "what-if" simulator and public portal design illustrate that non-expert interfaces must provide limited, meaningful choices and clear feedback (e.g. simple CO_2/€ indicators, colour scales, story-based narratives). Iterative user testing with diverse resident groups is crucial before scaling up to other neighbourhoods or cities.

6. **Phased, living-lab implementation reduces risk and increases learning**
   The three-phase approach (baseline setup → pilot execution → iterative calibration) allows issues to be detected early and corrected before full-scale deployment. Cities considering replication should treat their first LDT implementation as a living lab with built-in learning loops, rather than as a one-off IT project.

From these lessons, the following practical recommendations emerge for scaling:

- Start with one or two well-scoped neighbourhoods (e.g. a PED candidate area) before expanding city-wide.

- Reuse Almelo's data inventory template, governance principles and KPI framework as a starting point, adapting to local legal and institutional contexts.

- Align early with national/regional data platforms and EU initiatives (CitiVerse EDIC, EU LDT Toolbox) to ensure that local efforts can plug into a broader ecosystem.

- Reserve dedicated resources for community engagement and for maintaining the socio-technical dialogue between residents, municipal staff and technical partners.

6.3 Next Steps in 3DxVERSE

Within the 3DxVERSE project lifecycle, D8.1 is a bridge deliverable between concept/prototype work and full evaluation and replication:

- **Pilot Evaluation**
    - The KPIs, models, data pipelines and governance processes defined in D8.1 will be used to gather and analyse evidence of the Almelo-Aadorp pilot's performance.
    - D8.2 will assess the extent to which the LDT supports energy transition, citizen participation, trust and interoperability, and will identify strengths and gaps in the current implementation.
- **Replication and Scaling**
    - The workstreams and lessons summarised above will feed into D8.2, which will define concrete replication and scaling strategies for 3DxVERSE results.
    - Almelo's artefacts (ESDL models, ontologies, interface designs, engagement formats) will be packaged as reusable components and reference cases for other municipalities, both within and beyond the current pilot cities.
- **Contribution to European Digital Twin Ecosystems**
    - As the Almelo-Aadorp LDT matures, its datasets, models and governance patterns are intended to be shared with the EU Local Digital Twin Toolbox and related CitiVerse activities, contributing to a pan-European pool of open, interoperable assets.
    - Experience from Almelo will also inform discussions on standardisation, data spaces and ethical guidance for Local Digital Twins in sustainable living communities and Positive Energy Districts.

In summary, D8.1 demonstrates that a Local Digital Twin for a Positive Energy District can be implemented in a real village context in a way that is technically robust, socially grounded and interoperable with European frameworks. The next steps in 3DxVERSE will test, evaluate and scale this approach, turning Almelo-Aadorp from a single living lab into a reference blueprint for climate-neutral, citizen-centred neighbourhoods across Europe.

APPENDIX

APPENDIX A: RACI MATRIX

Workstream	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Spatial Planning & Permitting	Urban planners / Area developer	Municipality (Planning Department)	Residents (via Dorpscoöperatie), Water Board (canal aspects), Heritage experts	Wider public (general announcements)
Public Space & Mobility	Municipal Public Works Department	Municipality (overall)	Local residents and businesses (street & parking changes), public transport operators, logistics companies, safety services	City Council (periodic updates)
Housing Retrofits	Housing corporation or private homeowners	Housing corporation (for social housing) / Municipality (for private home facilitation)	Tenants, Dorpscoöperatie Aadorp	Neighbours (if construction causes nuisance)
Energy System (PED Operations)	Energy cooperative, utility partners (DSO, ESCO)	Municipality and/or asset owners (per energy asset)	Residents (hosting solar or other assets), Water Board (for canal heat / hydrogen O_2 use)	Funders and investors (performance monitoring)
Kanaalfront New Development (Ecology & Water)	Water Authority	Water Authority (lead for waterways)	Municipality, local nature organisations, residents	General public (environmental updates)
Construction Phasing & Access Management	Construction contractor(s)	Project developer	Affected businesses and residents (for scheduling), safety services (road closures/emergency plans)	General public (construction timelines)
Digital Twin & Data Governance	Tech partners (e.g. TNO, IT providers maintaining LDT)	Municipality / Project Lead	Dorpscoöperatie, DSO, Water Board (data inputs and use-cases)	Public (via open data portals/dashboards)
Financing & KPIs	Project Lead (consortium management)	Municipality / Consortium Lead (funding accountability)	Funders (banks, province - KPI targets, risk mitigation)	City Council and public (reporting, transparency)

APPENDIX B: EXTERNAL ACTORS

Domain	Actor / Organisation	Role & Responsibility
Electricity & Gas (DSO)	Coteq Netbeheer	Operate local electricity and gas distribution grids; manage connections, capacity planning and outages.
Electricity (TSO)	TenneT	High-voltage electricity transmission, congestion management signals and grid connection studies (where relevant).
Gas (TSO)	Gasunie Transport Services (GTS)	High-pressure gas transmission and interface with regional networks.
Hydrogen (Local Supply)	To be procured / pilot operator	Operate pilot hydrogen supply (electrolyser/trailer); handle permits, metering, safety and integration with heat/power.
Heat / ESCO	To be procured / municipal ESCO	Own and operate low-temperature heat assets; billing and customer service.
Drinking Water	Vitens	Drinking-water supply; network coordination during works; water quality safeguards.
Water & Sewage / Surface Water	Waterschap Vechtstromen	Stormwater, surface water and sewage treatment; permits and climate-adaptation measures.
Canal & Lock Authority	Rijkswaterstaat; Province of Overijssel (Sluis Aadorp)	Operation of the Twentekanaal and locks; permits for works near waterways.
Environmental Permits (VTH)	Omgevingsdienst Twente (ODT)	Environmental permitting, supervision and enforcement; noise, air and ecology checks.
Safety & Emergency	Veiligheidsregio Twente / Fire Brigade	Emergency access, hazard assessments and incident response planning.
Rail Infrastructure	ProRail	Rail corridor safety, permits and coordination of adjacent works.
Waste & Public Cleanliness	Twente Milieu	Waste collection and recycling logistics; adjustments during construction.
Housing Associations	Beter Wonen; Woningstichting Sint Joseph	Tenant liaison; renovation phasing; access arrangements for works.
EV Charging	To be selected (CPO/operator)	Public and semi-public charging infrastructure; smart charging/V2G integration.
Local Businesses & Logistics	SMEs and property owners along the canal	Access and loading arrangements; business continuity; potential co-investment.
Residents’ Representation	Dorpscoöperatie Aadorp	Resident engagement, co-design, feedback loops and community benefits.
Funding & Finance	Bank / Provincial or green fund	Project and asset finance; impact KPIs and reporting requirements.

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