INFRASTRUCTURE AND IMPLEMENTATION

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About ERA-Net Smart Energy Systems

ERA-Net Smart Energy Systems (ERA-Net SES) is a transnational joint programming platform of 30 national and regional funding partners for initiating co-creation and promoting energy system innovation. The network of owners and managers of national and regional public funding programs along the innovation chain provides a sustainable and service oriented joint programming platform to finance projects in thematic areas like Smart Power Grids, Regional and Local Energy Systems, Heating and Cooling Networks, Digital Energy and Smart Services, etc.

Co-creating with partners that help to understand the needs of relevant stakeholders, we team up with intermediaries to provide an innovation eco-system supporting consortia for research, innovation, technical development, piloting and demonstration activities. These co-operations pave the way towards implementation in real-life environments and market introduction.

Beyond that, ERA-Net SES provides a Knowledge Community, involving key demo projects and experts from all over Europe, to facilitate learning between projects and programs from the local level up to the European level.

www.eranet-smartenergysystems.eu

1 EXECUTIVE SUMMARY

The Digicities project developed a semantic data platform to address persistent barriers to energy data exchange at the urban scale: fragmented datasets, inconsistent terminology across domains, labour-intensive data preparation, and limited traceability of the assumptions that underpin energy planning studies. The platform provides a shared environment where data publishers, digital service providers, and energy planners interact with semantically structured data layers through a modular web application.

The core architecture integrates five components:

- a Microsoft Azure cloud tenant
- a Streamlit-based application with CI/CD pipelines
- an Ontotext GraphDB triplestore for semantic storage
- NextCloud for file-based data product management
- Keycloak for federated identity and access control.

Nine modules complete data workflow: ontology management, digital replica creation and exploration, SPARQL query execution, semantic data product handling, service registration via YAML specifications, scenario construction from multi-source component instances, assumption-based scenario modification with provenance tracking, and API submission to external analytical services. Three design decisions distinguish the platform from conventional approaches to energy data infrastructure. First, a flexible, service-driven ontology allows developers to define lightweight extensions specifying only the components and attributes their applications require, rather than adopting complex domain ontologies (CIM, SAREF, CGMES) in their entirety. Systematic mapping to established standards preserves interoperability when cross-system integration is needed, without imposing universal conformance. Second, semantic data products package machine-readable RDF descriptions with associated resource files (CSV time series, GeoJSON geometries, weather data) into self-contained, discoverable units that eliminate ambiguity about data content, units, and provenance. Third, scenario management with full assumption traceability enables planners to construct, compare, and submit scenario variants to external services while maintaining a complete record of modifications.

Stakeholder assessment revealed that digital service providers see immediate value in reduced data integration workloads, improved API data quality, and scalable multi-scenario handling. Energy planners and municipal stakeholders, however, identified migration costs and workflow transition as primary adoption barriers, with concrete case studies and quantified time savings required before commitment. The project consortium is considering releasing the full software stack as open source, which would enable community-driven refinement of the tooling and data ingestion methods and broaden the platform's potential user base, though it would preclude certain commercial licensing models for the platform itself. The workspace-based architecture aligns with data space principles (IDSA, GAIA-X, European Data Strategy) emphasising data sovereignty and can evolve toward fully federated storage where users connect their own cloud infrastructure. This deliverable details the design, architectural decisions, module-level implementation, and alignment with international digitalisation initiatives that informed the platform's development.

2 INTRODUCTION

Digicities is a bottom-up, use-case driven project to demonstrate how information technologies can improve the exchange of data for energy planning and operation. This section introduces some of the core terms of the activities covered in the project.

2.1 What is digital transformation?

Digital transformation has been defined as: "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies" (Vial, 2021). As a result, the digital transformation affects almost all elements of our daily lives. In Switzerland, the federal council has implemented a strategy for a "digital Switzerland" that outlines the benefits and challenges across many sectors and has urged all stakeholders to approach relevant implementation projects and cross-sectional topics (BFS, 2020).

The federal ministry of Austria has also implemented a "Digital Austria" strategy, where the benefits of digitalisation and the necessary development in the key action areas (Economy, government, education, health and care, security and infrastructure, etc.) are outlined. Moreover, the strategy for artificial intelligence "AIM AT 2030" was published in 2021 by the Austrian federal government. This strategy addresses the opportunities and challenges of artificial intelligence (AI), e.g. the opportunities of digitalisation include a contribution to climate change mitigation and post-pandemic economic recovery; the challenges include data security, equal rights, and preventing discrimination. Because of the rapid development of AI technologies and their applications, "AIM AT 2030" sets guidelines in which the use of AI in Austria should develop. (Federal Ministry Republic of Austria Finance, n.d.).

2.2 What is the clean energy transition?

The term clean energy transition refers to the process of reducing our dependence on fossil fuels by switching to clean fuels through increased uptake of renewable energy supply options and energy-efficient measures and electrification of energy end-uses. The transition to a sustainable future includes an evolution of how we generate and use energy.

The Austria's Climate and Energy Strategy (referred to as #mission 2030[1]) and subsequent updates[2] aligned with the Climate neutrality goal 2040. It sets national framework for achieving a secure, sustainable, and climate-neutral energy system. The aim of the strategy is to achieve climate neutrality by 2040 (net-zero target) by rapidly expanding renewable energy, phasing out fossil fuels, increasing energy efficiency, and enabling a socially just, secure, and innovative clean energy transition. However, considering the ongoing discussion among EU countries, that

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[1] Austrian Climate and Energy Strategy

[2] Austria's climate action strategy

the target of climate neutrality by 2040 is too ambitious and might affect the economic competitiveness Europe's, the EC might soften the 2040 target[3].

The Swiss Energy Strategy 2050 aims to achieve net zero greenhouse gas emissions by 2050 (SFOE, 2022).

2.3 The role of the digital transformation in the energy transition

Energy systems and their networks are inherently complex, comprised of multiple stakeholders, technologies and actors. The ongoing clean energy transition will result in increasing share of intermittent renewable energy sources (RES) and an increasing number of decentralised, small-scale systems with active energy prosumers. To ensure stability and energy security, there is a need for smart, interconnected energy systems capable of dynamically responding to fluctuations in demand and resource availability, thereby addressing emerging flexibility gaps.

The evolving spatio-temporal dynamics of these systems require a higher level of digitalisation. Digitalization is an enabler of the clean energy transition and is expected to play a key role to reach a sustainable and resilient urban energy system (Dekeyrel and Fessler, 2024). It enables the optimisation of energy supply and demand, enhances overall system performance, and facilitates sector coupling across domains such as buildings, energy, and mobility, unlocking significant energy efficiency and decarbonisation potential.

2.4 Core terms

2.4.1 Smart cities

At the urban scale, the smart city vision, characterized by resilience, resource efficiency, sustainability, and carbon-neutrality, requires innovative, cross-sectoral solutions enabled by digitalisation. Sustainable urban energy systems are central because of their strong interdependencies with transport, water, food, health, and other infrastructures (International Energy Agency, 2021; O'Dwyer et al., 2019). Ensuring reliable energy services in a socially just, economically affordable, and environmentally sound manner is therefore essential for sustainable urban development (European Committee of the Regions ., 2024).

However, the involvement of highly complex, multi-actor energy systems poses significant challenges for real-world implementation. These challenges are primarily driven by limited data interoperability, restricted data accessibility, and the absence of clear and trusted frameworks for data sharing among stakeholders.

2.4.2 Internet of Things (IoT)

The Internet of Things (IoT) aim an intelligence world that is connected things themselves via internet without human supporting. They communicate each other

[3] Austria walks back support for EU's 2040 climate target

and decide themselves. The IoT collaborate with A.I and Edge Computing. The things can be sensors, actuator, smart phone etc. The IoT can apply several domains such as Smart Home, Smart City, Smart Factory etc.

3 CHALLENGES TO THE DIGITAL TRANSFORMATION

3.1 Semantic interoperability

Data streams between system operators, consumers, producers and other stakeholders of the energy system are becoming larger and more diverse, with new requirements on data exchange being introduced by the efficient operation of buildings and the integration of new technologies into the energy system. Semantic interoperability between applications like building energy control, grid operation and energy system modelling is therefore fundamental to the digitalization of energy infrastructure within the energy system and buildings themselves (Pritoni et al., 2021). The following section provides an overview to currently applied concepts in the digitalization of energy systems and building energy infrastructure and introduces the infrastructure implemented in the Austrian use cases.

3.2 Digitalization and physical scope of data (device/ building/ district/city)

The level of digitalization and semantic interoperability is not consistent or insufficient across the different hierarchy levels, e.g., building level or city level, of the energy system. Different use cases in building energy modelling and operation traditionally apply use case specific data schemes. Semantic interoperability between these schemes is not always given, as demonstrated by Pritoni et al., who provide a review of metadata schemas on the building level and their interoperability (Pritoni et al., 2021). The work concludes with recommendations towards the implementation of centralized databases and search engines to make existing ontologies more accessible and comparable, and finally the harmonization and standardization of data schemas across stakeholder groups, as the interoperability between the investigated schemas was found to be insufficient. Furthermore, the level of digitalization and semantic interoperability is not consistent across the different hierarchy levels, e.g., building level or city level, of the energy system.

3.3 Data standards and ontologies

To close this gap and enable the exploitation of energy data on multiple levels for decision making, Li et al. introduced an energy management-KPI ontology for the building and district level (Li et al., 2017). The ontology developed by Li et al. builds on existing ontologies and concepts that were extended to allow the calculation of key performance indicators (KPIs) that serve the defined stakeholders of district energy systems, e.g., district energy managers, building energy managers. The ontology was successfully demonstrated in data exchange from heterogeneous sources and subsequent KPI generation on the district level, aggregating and linking data from individual buildings. Going one step further, Li et al. also proposes an information sharing strategy based on the above-described ontology, outlining potential real implementations of local dispatch procedures based on that common ontology (Li and Hong, 2022). The results of the analysis demonstrate the potential of integrated dataspaces and the proposed information sharing strategy to benefit local energy stakeholders, however, lack real time implementation capabilities. Besides the benefits, there are also numerous challenges and risks coming along with the digitalization of the energy system such as cyberattacks, data privacy or growing energy use of digital technologies (see Figure 2 later).

3.4 Data Access

Another challenge for the access of data is the data protection rule for e.g., energy data from residents. But in these terms, there are several ways in which residents can be encouraged to consent to sharing their data, including via transparent and customisable agreements, anonymised data collection, crowdsourcing, and information campaigns on the positive public benefits that data can provide. Hereby, national governments can assist cities in creating standardised procedures and frameworks. Figure 1 shows the data flow process in a smart city. The data will be measured and collected by sensors (e.g.: smart meters) and in the next step the data will be processed by e.g., big data processing. This data can be used for example for data intelligence applications (e.g.: Digital twins), business applications (e.g., web apps) and forwarding decarbonisation strategies (International Energy Agency, 2021).

3.5 Data Silos

On a more general level of abstraction, the concept of real-time linked databases, as described by Curry (Curry, 2021) provides an interesting approach to cost effective integration and use of data streams originating from energy infrastructure and buildings. Dataspaces recognize the heterogeneity across datasets and promote a pay-as-you-go approach to the integration of datasets, meaning that the resource intensive integration and linking between data sources takes place according arising needs, rather than upfront. This results in databases that are loosely integrated in areas where full semantic integration is not required and more integrated in applications that are immediately needed, whereas all datasets are bundled in the same data platform. (Curry, 2021) also gives an outlook on future challenges towards dataspaces. These include large-scale decentralised support services, trusted data sharing, governance models, and finally human centricity.

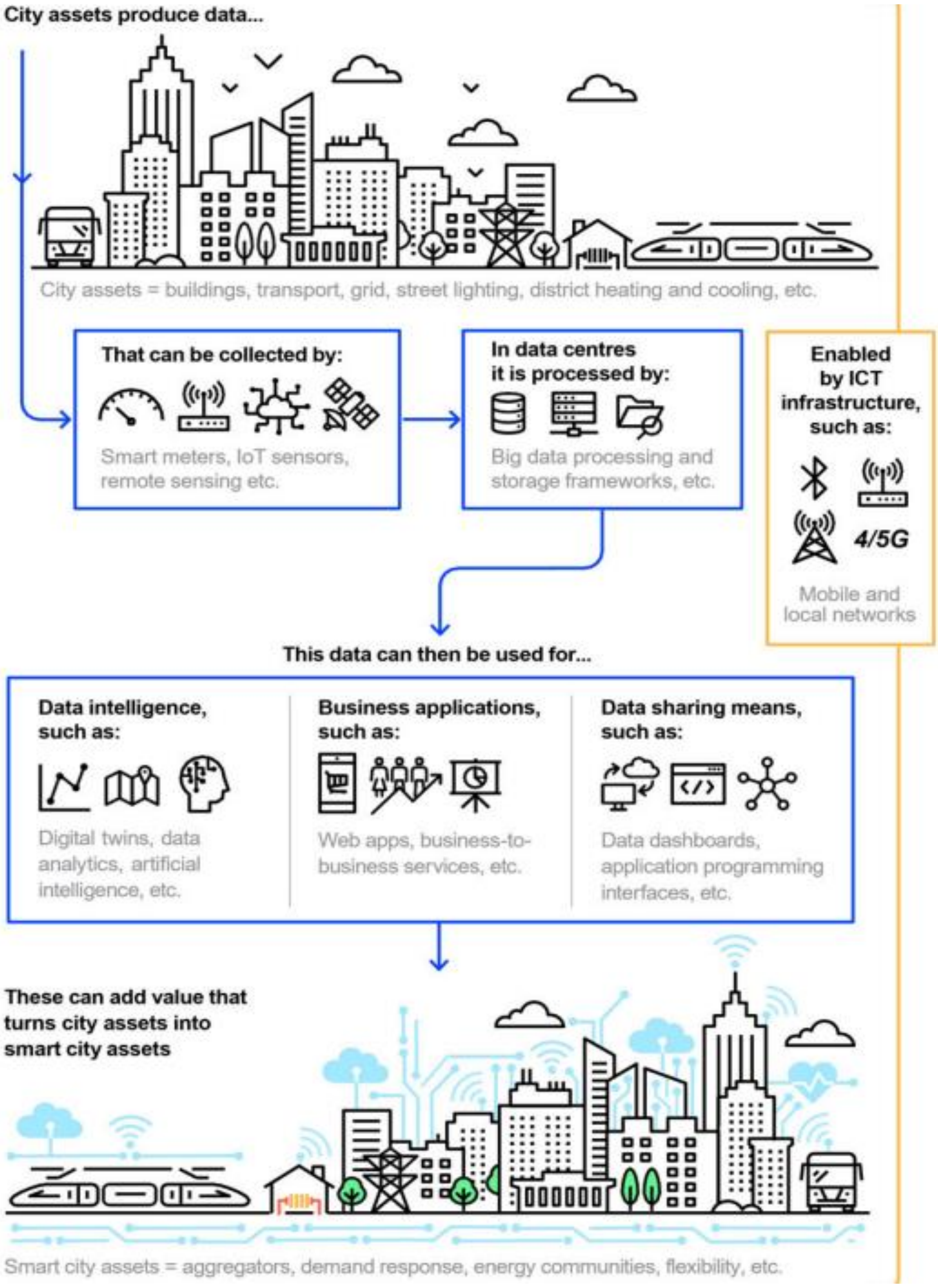


Figure 1: Data flow scheme of smart cities (IEA, 2021)

4 DIGITALISATION POLICES AND INITIATIVES

4.1 International

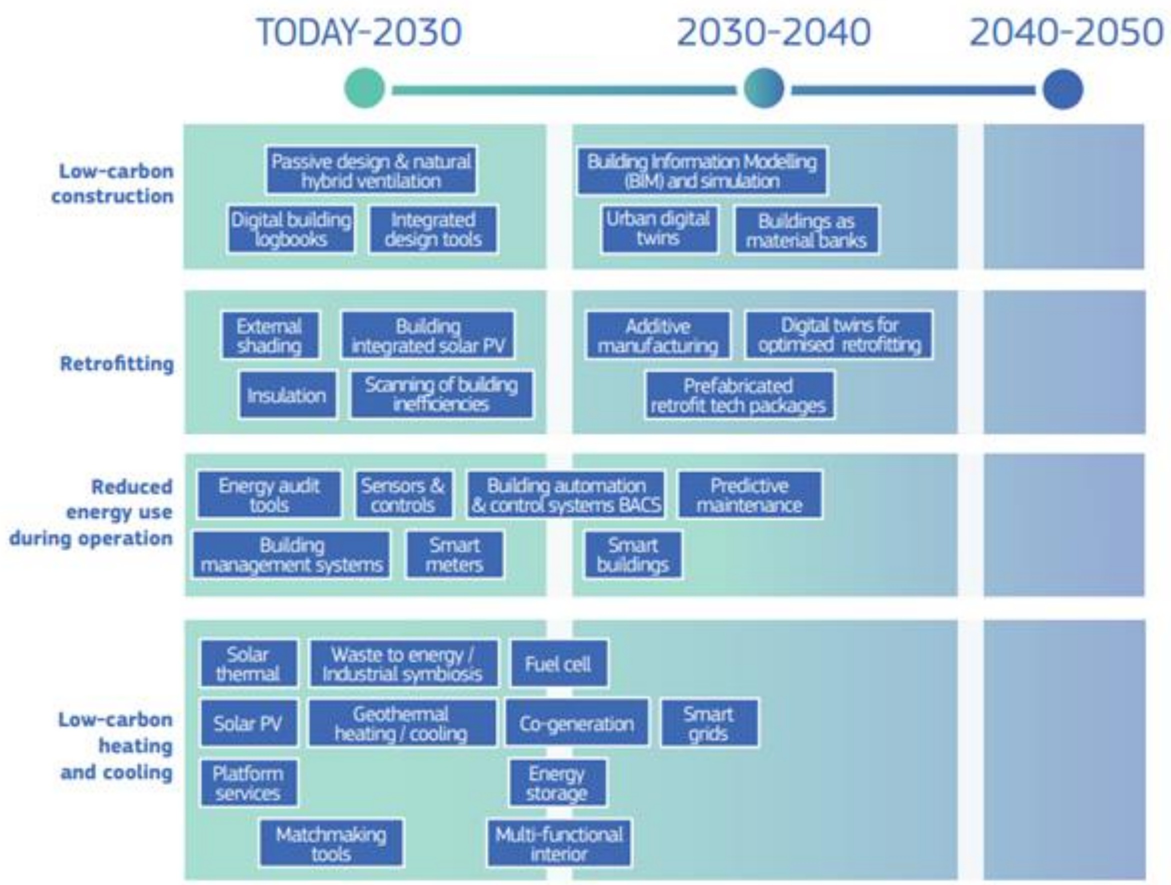
4.1.1 International Energy Agency (IEA)

The IEA in 2021, published the "Empowering Cities for a Net Zero Future", which covers issues and challenges of cities, that are facing on climate action. Because of the fact, that 50% of the population in 2021 live in cities and account for 70% of global CO_2 emissions, cities will have a big role to achieve a net-zero world. Moreover, in this report is mentioned, that digitalisation can support cities making them smarter in case of better-informed decisions, especially on sustainable urban planning and operational issues. Beside of the benefits of digitalisation, also challenges and risks of using digital technologies for decarbonisation are pointed out in this report. All barriers and challenges are clustered in main topics, e.g. data challenges, and the solutions were also provided by this report (Figure 2) (International Energy Agency, 2021).

	Challenges	Solutions
Data challenges	• Limited use of existing data • Lack of access to data • Barriers to data sharing • Insufficient data interoperability • Privacy and security concerns	☑ Data-sharing platforms ☑ Harmonisation standards ☑ Data protection frameworks, transparent communication
Insufficient co-ordination	• Lack of dialogue and mechanisms for joint planning between national, regional and local governments • Interdepartmental silos • Lack of dedicated resources	☑ Develop communities of practice ☑ Create knowledge-sharing platforms ☑ Create cross-cutting networks ☑ Create special-purpose vehicles
Lack of capacity	• Limited access to digitalisation skills and capacity • Limited bandwidth to tackle new opportunities	☑ Create initiatives to attract capacity and skills ☑ Develop opportunities for knowledge exchange ☑ Develop training and upskilling programmes
Access to finance	• Limited revenues • Inability to take on debt • Lack of capacity to develop investment-grade projects or access existing clean energy or climate finance	☑ Stimulate public–private partnerships ☑ Support the creation of new instruments e.g. green bonds ☑ Redirect funding and develop dedicated financing vehicles ☑ Introduce training to develop bankable projects ☑ Support the creation of revenue-generating business models
Digitalisation risks	• Cybersecurity • Environmental impact of digital technologies • Lack of equitable access and inclusivity	☑ Develop cyber security frameworks and guidelines ☑ Create options for circularity ☑ Build capacity and create inclusive policies and projects

Figure 2: Challenges and barriers of digitalization for decarbonization of cities (IEA, 2021)

Figure 2 shows that data is a challenge for digitalisation. Hereby, national and regional regulations can support open access to data. For example, the German federal state of Baden-Wuerttemberg has recently passed a new climate act, which requires utilities and industry to share data on demand, the location and capacity of grid infrastructure, potential excess heat sources and other variables, specifying that cities have the right to use all available data, including personal data. Figure 3 illustrates envisioned innovation timelines for the deployment of digital technologies and concepts to transforming building and the built environment toward climate neutral cities.



Source: JRC experts workshop, GlobalABC, IEA, and UNEP (2020), European Academies Science Advisory Council (2021)
Note: These are approximate innovation timelines based on expert discussions and indicate when a certain technology might be available to the market.

Figure 3: envisioned innovation timelines for digital technologies diffusion at city scale.

4.1.2 EU

Digital and green transition are highly interlinked in the European transition strategy. The notion of "twin transitions" is presented in the JRC publication "Towards a green and digital future" (European Commission. Joint Research Centre., 2022). According to the EU, digitalisation could support energy transition at different level. For example, real time knowledge can be provided through monitoring and tracking, the energy efficiency can be improved through simulation and forecasting, and the developed digital systems management can help coping with the increasing complexity of energy systems.

The current state of the art in urban energy system digitalization in the European Union was recently reviewed by Alpagut *et al.* After outlining the potentials, drivers, and barriers for urban energy system digitalization, the authors provide policy recommendations as well as 3 development scenarios until 2040. While the potential implications digitalization was found to be uncertain, due to barriers and limitations regarding data and integration between public and private sectors, scenarios that reflect possible pathways have been drawn within expert workshops. The scenarios indicate that positive impacts of digitalization for the integration and investment in renewable energy technologies are possible. However, their full exploitation is linked to implementation of strong data policies and regulations regarding data interoperability (Alpagut et al., 2022). Figure 4 shows and compares the developed scenarios. The review performed on the Smart City and Communities (SCC) in this report categorises the digitalisation concepts and innovations within 3 categories: the supply (i.e.: the primary energy), the conversion (i.e.: the integrated infrastructure), and the demand (i.e.: the final energy). The results highlight that most of the current European projects included in the review focus on the smart appliances urban digital platforms, energy management techniques and optimisation of energy systems.

	Scenario 1. Slow and reluctant digitalisation of UES.	Scenario 2. Private sector reaps digitalisation benefits	Scenario 3. Open, trusted, efficient digitalised UES
BUILDINGS (DEMAND AND SUPPLY SIDE)	**Slow digitalisation** due to concerns on data privacy, mistrust on AI, and difficulty of participation in energy markets. **RES have been adopted but are not being optimised**	Private companies have service contracts in most buildings, and have **optimised efficiency**, **renewable energy production** and **flexibility management**, with no upfront costs for building owners.	SRI has triggered investments in **buildings' digitalisation**. Widely adopted solutions for **renewable energy integration** and **participation in energy markets, including flexibility**.
MOBILITY (DEMAND SIDE)	Traditional **active mobility** (cycling, walking) and **car-free zones** are increasingly adopted in cities. **Digitalised** mobility solutions are mostly used for **public transport**.	Cost effective **private MaaS** is displacing public transport. Complex management of urban mobility as the pace of **digitalisation within the public sector** is comparatively very **slow**.	Cities operate efficient **urban mobility platforms**. Very successful and cost effective **MaaS solutions** have been deployed and widely in use, together with **multimodal solutions** for public transport.
INTEGRATED INFRASTRUCTURE	**Slow** penetration of **distributed storage and flexibility solutions**, and **low participation** of citizens in **energy markets**.	ESCOs and large utilities have control of most of the **UES** through **service contracts**. They efficiently manage **renewables, storage, flexibility assets**.	**Citizens fully participating in the energy market. High rate of distributed RES and storage**, 100s GW **flexible capacity** in operation in cities.
CITIZEN ENGAGEMENT	Low	Medium	High
DATA AVAILABILITY AND DATA ACCESS	Low	Medium	High

Figure 4 Digitalization scenarios as elaborated in a recent EU publication on urban energy system digitalization (Alpagut et al., 2022)

4.1.3 EC's Action plan on energy system digitalisation

In October 2022, the European Commission published its Action plan on the digitalization of energy systems (European Commission, 2022). It is likely to support the REPowerEU initiative4 aiming to accelerate renewables and hydrogen penetration in the power sector. The action plan covers five areas linking energy and digitalization:

- Development of a European data-sharing infrastructure and framework for innovative energy services. It includes a common European energy data space enabling the share and use of energy data. The dedicated working group Data for Energy (D4E) will work at implementing an act on interoperability, non-discriminatory and transparent procedures for access to metering and consumption data.

- Empowering citizens to participate in the energy market: digital tools will play an essential role in developing energy communities. The commission will work on identifying digital tools to support peer-to-peer energy sharing and develop experimentation.

- Climate neutrality in the ICT sector: The ICT sector accounts for 7% of global electricity consumption and is expected to reach 13% by 2030. To reduce the energy consumption of the sector, measures will be implemented to address the energy and resources consumption over the entire value chain and the key emerging additional sources of ICT-related energy consumption (e.g., datacenters, cryptocurrencies).

- Strengthening cybersecurity and resilience in the energy system: the commission will work on a Cyber Resilience Act, that will aim at harmonizing the cybersecurity rules of energy systems and services.

- Promoting investments in digital electricity infrastructure: the European Commission will support the TSOs and DSOs in developing a digital twin of the European electricity grid.

4.1.4 GAIA-X

GAIA-X is a European initiative, jointly launched by Germany and France in 2019, that aims to establish a federated and secure data infrastructure grounded in the principles of openness, transparency, interoperability, and data sovereignty (Braud et al., 2021). Rather than creating a single centralized cloud, GAIA-X defines a set of common specifications, rules, and a verification framework that allow multiple cloud service providers and data owners to connect within a trusted ecosystem. Participants retain control over their data deciding what is shared, with whom, and under what conditions while benefiting from cross-sector data exchange and compliance with European regulatory standards such as the GDPR[5]. Key aspects of the GAIA-X framework focused on a federated, interoperable architecture that

[4] https://commission.europa.eu/topics/energy/repowereu_en

[5] https://gaia-x.eu/

enables decentralized data storage and processing while ensuring seamless data exchange across systems. It prioritises data sovereignty, allowing data owners to retain full control over how their data is accessed, used, and shared. The framework promotes interoperability through common standards and protocols, ensuring compatibility across sectors and borders.

Security and trust are core principles, supported by robust protection mechanisms and certification schemes that ensure compliance with data protection, transparency, and governance requirements. GAIA-X also fosters a collaborative digital ecosystem and operates under an open governance model, enabling broad stakeholder participation and innovation.

5 AIMS AND OBJECTIVES OF DIGICITIES

DIGICITIES has established a framework to enable the exchange of data between different of stakeholders representing various domains across the digital value chain. At the centre of the work is the development of structured interconnected digital urban layers that harmonize the processing, storage and use of data sources. These semantically structured data layers have been integrated into a data exchange framework to support stakeholders from utilities to citizens. The framework responds to the needs of real living labs in Austria and Switzerland represented in the developed and established use cases in both countries. The considered use cases enable addressing a range of different research questions across the living labs and demonstrate transferability of the framework. The framework facilitates sector coupling, new value chains and application of latest innovation from the information and communications technology domain.

This work targets the barriers to the accessibility and exchange of energy-related data at urban scale (building, district, city). It aims to provide clear opportunities and incentives for owners and generators of data to share their information. In addition, they receive insights on how to use the data to better manage the energy resources of their city and buildings. The project worked on:

- Providing a digitization framework that facilitates the energy system transformation and support cities’ decision making in achieving their energy and climate goals.
- Addressing the lack of availability and transparency surrounding open data and models in the energy sector (specifically for urban and district modelling).
- Overcoming security and privacy issues encountered when providing data.
- Investigating new incentives for sharing of metered and energy-related data.
- Developing decentralized structured, digital layers to create new business opportunities across the value chain.

With focus on the Austrian and Swiss use cases developed within the project the activities focused on the:

- Development and implementation of a data architecture.
- Development of federated queries across the datasets.
- Building Level Service Definitions: development of generic data acquisition services on building level based on open and standardized APIs to maximize the usability of data and avoid data islands. A critical analysis towards data privacy and necessary measures that need to be implemented is also done within the data architecture
- Reporting on alignment with initiatives, best practices and findings from implementation.
- Inter-project and transnational knowledge exchange across working groups.

6 METHODOLOGY

The platform is an interface to work with the semantic layers. This section describes the architecture adopted in the prototype platform. The primary functionality is a secure environment that allows users to access their data; however, the platform also contains a set of modular functions to allow the users to work with the semantic layers. This section describes the core architecture of the platform, the different modules and the interface with third party applications.

6.1 Core architecture

The core architecture of the Digicities platform is comprised of the following components:

- Microsoft Azure tenant
- Repository containing the application (Streamlit) and deployment pipelines
- RDF Triplestore containing the semantic layers (Ontotext GraphDB)
- Cloud storage (NextCloud)
- User identity and access management (Keycloak)

The organisation and interaction of these components is shown in Figure 5.

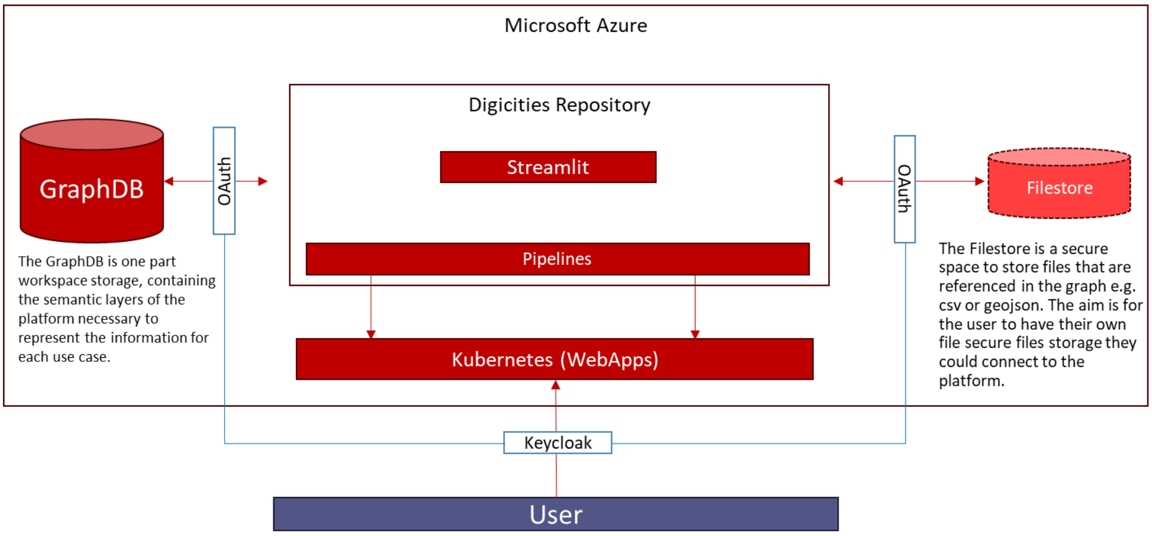


Figure 5: Core architecture of the DIGICITIES platform.

The following section gives an overview of the submodules of the platform and their functionality. A tutorial of the platform is provided in the supporting documents.

6.2 Ontology Manager

The Ontology Manager provides a comprehensive platform for building, extending, and maintaining the Digicities core ontology, abstracting the complexities of RDF/OWL syntax whilst enabling semantic model development. The system maintains clear separation between the core ontology and user-generated extensions, storing these separately whilst providing seamless merging capabilities for deployment.

6.2.1 Component and Attribute Management

Users can define hierarchical component structures by specifying labels and parent classes, with the system automatically managing inheritance chains and creating associated attribute categories. Components can be reorganised through parent relationship modifications, with the platform updating all dependent structures. The platform supports the multiple attribute types detailed previously—Physical, Cost (Simple and Unit-Based), Curve, Categorical, Geospatial, Custom Physical Ratio, Event, and Simple Value—each with specialised properties and validation rules. When attributes are linked to components, the system automatically creates necessary property definitions and ensures proper categorisation within component attribute hierarchies, handling the complex RDF graph structure behind simple selection interfaces.

6.2.2 Mapping and Interoperability

The Ontology Manager provides comprehensive mapping capabilities for external ontology integration. Users can upload external ontology files and create alignments between Digicities concepts and external vocabularies, supporting the equivalence, hierarchical, and similarity relationship types described in the interoperability framework. These mappings are stored separately and managed independently, allowing simultaneous connections with multiple external standards. The interface presents internal and external concepts side-by-side, enabling informed mapping decisions.

6.2.3 Deployment and Exploration

Query-based interfaces enable users to explore components, attributes, and properties throughout the development process, presenting information in structured tables that show inheritance relationships, labels, and metadata. Once complete, ontology extensions can be deployed directly to GraphDB triple store repositories, with the module handling authentication, serialisation with proper namespace bindings, and upload to named graphs, enabling immediate support for data ingestion and querying operations across the platform.

6.3 Replica Builder

The Replica Builder enables users to create digital replica that conforms to the ontology structure defined in the Ontology Manager. This module creates instances that conform to the ontology. These instances are digital replicas of real-world components and their relationships, generating RDF graphs that populate the workspace.

6.3.1 Instance Creation Workflow

The module begins by loading the ontology from GraphDB, automatically discovering available component types and their permissible attributes. Users create component instances by selecting a component type and providing a unique identifier and label. The system generates URIs based on configurable patterns and organizes instances by type for easy navigation. Instance management includes search and filtering capabilities, with automatic validation to prevent duplicate identifiers.

6.3.2 Attribute Configuration

Users configure instance attributes through a type-specific interface that supports multiple attribute types including physical measurements with units, dynamic time series references, categorical values, temporal events, costs, curves, resource paths, and annotations. The system constrains attribute selection to only those defined in the ontology for each component type, ensuring semantic validity. Input fields adapt dynamically based on attribute type, presenting appropriate validation and data entry options.

6.3.3 Relationship Management

The Link Manager enables users to define relationships between instances using properties from the ontology. Users select source and target instances and choose from available relationship properties such as spatial containment, connectivity, or supply relationships. All links are validated against ontology constraints and stored in the system description graph.

6.3.4 Data Import and Deployment

For bulk data loading, the module provides Excel import functionality that processes multi-sheet workbooks where each sheet represents a component type. Users can preview generated RDF, validate against ontology constraints, and choose to merge with or replace existing data. The deployment interface offers two modes: append mode adds new instances to existing graphs, while replace mode clears and rebuilds graphs. Users can preview generated Turtle serialization, download for backup, and upload directly to GraphDB repositories with automatic namespace binding and transaction management.

6.4 Replica Explorer

The Replica Explorer provides an interactive interface for browsing and analyzing component instances stored in the knowledge graph. The module automatically discovers all component types with instances, presenting them in a dropdown menu with instance counts. Users select a component type to view comprehensive tables displaying instances and their attributes, with support for multiple attribute types including physical measurements with units, costs with currencies, categorical values, temporal data, time series references, curve data points, geospatial information, and custom unit ratios. The interface provides search and filtering capabilities, automatically formats values for readability, and enables data export as CSV files. For curve attributes, users can generate interactive visualizations with statistical summaries.

6.5 Query Manager

The Query Manager provides an interface for creating, editing, executing, and managing SPARQL queries to interrogate the knowledge graph. Users can create new queries or select from saved workspace-specific queries stored in global Nextcloud storage, with default query templates provided based on workspace type (e.g., Renewable Energy, Municipal Infrastructure, Building Management). The query editor allows users to write and modify SPARQL queries with syntax highlighting, then execute them against the connected GraphDB repository. Results are displayed in interactive tables with configurable namespace replacement and path extraction options to improve readability by converting long URIs into shortened prefixes or local names. Users can save, update, or delete queries with overwrite protection, and export results as CSV files in either formatted or raw format. The module maintains workspace-specific query collections and namespace configurations, enabling users to build libraries of reusable queries for common data exploration and analysis tasks across their digital twin knowledge base.

6.6 Data Products

The Data Products module enables users to load, explore, and visualize self-contained data packages that combine semantic TTL descriptions with associated resource files. Data products are organized as folders containing a TTL file defining component instances and a resources subfolder with related data files such as time series CSVs, GeoJSON geometries, or weather data.

6.6.1 Loading and Management

Users can load data products from two locations: open data products available globally to all users, and private data products specific to their workspace. The module connects to Nextcloud storage using environment-based authentication, automatically discovering available data product folders in both locations. When loaded, the system parses the TTL file to extract component definitions and their attributes, then lists available resources in the resources subfolder. Users see summary metrics showing total products loaded, component counts, and available resource files, with the ability to select specific products for detailed exploration.

6.6.2 Data Exploration

The explorer interface presents data products with expandable component listings organized by type. Users can filter components and view detailed information including URIs, labels, attribute counts, and linked resources. Attributes are grouped by category (physical, cost, geospatial, dynamic, categorical, etc.) and displayed in tables with formatted values, units, and resource indicators. The interface handles multiple attribute types with appropriate formatting, converting URIs to readable values and truncating long strings. Users can access raw JSON views of attribute data and download component information for external analysis.

6.6.3 Visualization and Analytics

The module automatically determines appropriate visualization types based on component attributes. For geospatial data with latitude/longitude coordinates, it renders interactive maps showing component locations. Time series attributes trigger line charts with range sliders and statistical summaries showing min, max, mean, and data point counts. Curve data is visualized with scatter plots and data point tables. Components without specialized data types display static attribute tables. The visualizer loads resource files on demand, parsing CSVs into dataframes, processing GeoJSON for mapping, and handling other file formats. Users can download visualizations and underlying data, navigate between components, and switch between visualization and detailed attribute views to explore data from different perspectives.

6.7 Service Registration

The Service Registration module enables users to create YAML configuration files that define service requirements by mapping ontology components and attributes to service input fields. Users connect to GraphDB to load available components and their valid attribute mappings from the dici_onto ontology, ensuring only semantically correct configurations can be created. The interface supports building hierarchical component structures with parent-child relationships, where users select component types and organize them using automatically generated link patterns. For each component, users configure which attributes to include and designate them as Static, Historic, Live, or Future data types, with multiple types selectable simultaneously. A validation system checks all component-attribute pairs against ontology mappings, displaying errors, warnings, and valid configurations with actionable suggestions for fixing issues. Users can customize YAML field names while maintaining ontology references, preview the generated structure, and export configurations as YAML files for service integration and automated data extraction workflows.

6.8 Scenario Builder

The Scenario Builder enables users to construct scenario configurations by selecting component instances from data products and knowledge graphs that satisfy the data requirements specified in service YAML files created through the Service Registration module. This module bridges service definitions with available instance data, allowing users to create multiple scenario variants of the same system for different analysis contexts.

6.8.1 Service-Driven Configuration

Users select a service definition YAML file that specifies required component types, attributes, and relationships. The system parses the YAML to extract component requirements including hierarchical link patterns, required attributes with nested properties and time series references, and temporal data specifications. The interface displays which component types are needed and validates whether selected instances provide all required attributes, ensuring scenario completeness before export.

6.8.2 Multi-Source Instance Selection

The builder integrates component instances from multiple sources: the workspace knowledge graph containing custom components, private TTL data products specific to the workspace, and global TTL data products shared across all workspaces. Users enable desired data sources and select component instances through a batch selection interface, with the system tracking data provenance and validating each instance against service requirements. This allows flexible scenario construction even when the workspace knowledge graph is empty, relying entirely on data products if needed.

6.8.3 Relationship Definition and Validation

Users define relationships between selected components according to link patterns specified in the service requirements, such as parent-child hierarchies or connectivity relationships. The validation system ensures all required attributes are present in selected instances, checks nested property requirements for complex attributes, and verifies that component relationships match service specifications. Components are color-coded by validation status, showing which instances fully satisfy requirements and which have missing attributes.

6.8.4 Scenario Serialization and Variants

The system generates scenario-specific TTL files containing the selected component instances, their configured attributes and relationships, and service-specific metadata. These scenario graphs exist as separate entities alongside the original instance data, enabling users to create multiple scenario variants of the same system for different analytical purposes, temporal contexts, or configuration alternatives. Each scenario is serialized as an independent TTL file that can be uploaded to the knowledge graph, NextCloud or downloaded for conversion for external services, maintaining clear separation between base instance data and scenario-specific configurations.

6.9 Assumptions

The Assumptions module enables users to create scenario variants by systematically modifying component attributes in baseline scenarios through predefined assumptions or manual edits. This allows exploration of different system configurations, temporal changes, or what-if analyses while maintaining clear provenance tracking from baseline to modified scenarios.

6.9.1 Baseline Loading

Users load baseline scenarios from the workspace scenarios folder (created by Scenario Builder) or upload TTL files directly. The system parses baseline scenarios to extract components, attributes, and relationships, displaying summary metrics showing component counts, types, and total attributes. Loaded baselines serve as the foundation for generating modified scenario variants through assumption application or manual modification.

6.9.2 Predefined Assumption Application

Users select from predefined assumptions that target specific component types and attribute categories such as physical properties, costs, or geospatial data. Assumptions can be single modifications creating one variant or series modifications generating multiple scenarios across timesteps for temporal analysis. The system validates assumption compatibility against baseline components, showing which assumptions can be applied and how many components will be affected. Applied assumptions automatically modify relevant attribute values according to specified modifiers like percentage changes, absolute adjustments, or scaling factors.

6.9.3 Manual Modification

Users can manually edit individual component attributes through an interactive interface, selecting components by type or search term and modifying attribute values directly. The system tracks pending modifications with before/after comparisons and percentage changes, allowing users to review and adjust edits before generating scenarios. Manual modifications support all attribute types including physical measurements, costs, categorical values, and geospatial data, with appropriate input controls for each type.

6.9.4 Scenario Generation and Export

Modified scenarios are generated as independent TTL files with full traceability, including metadata about applied assumptions, modification types, and affected component counts. Users can view generated scenarios with modification logs showing which attributes changed and by how much, preview TTL content, and export scenarios individually, as ZIP archives, or upload directly to the workspace scenarios folder. Each generated scenario exists as a separate entity that can be used independently for analysis, uploaded to the knowledge graph, or serve as a baseline for further modifications, enabling iterative scenario exploration and variant creation.

6.10 API Submission

The API Submission module enables users to convert scenario TTL files into service-specific JSON/YAML formats and submit them to configured external APIs for analysis, simulation, or optimization. The module handles the complete workflow from TTL conversion through submission to result management, with automatic result saving to NextCloud for persistence and review.

6.10.1 Service Configuration and Templates

Users configure API endpoints by selecting from service templates loaded from NextCloud or local files, specifying connection details including URLs, HTTP methods, authentication credentials, and timeout settings. The system supports multiple authentication types including bearer tokens, API keys, basic authentication, and environment-based JWT tokens. For the pilot we configured a fast set up for CESARP building simulation and Sympheny regional analysis, automatically configuring endpoints with appropriate defaults while allowing customization of polling intervals, retry limits, and authentication parameters.

6.10.2 TTL to JSON/YAML Conversion

Users select scenario TTL files from the workspace scenarios folder or upload files manually, then choose target service templates for conversion. The conversion engine parses TTL content to extract component instances, attributes, and relationships, mapping them to service-specific data structures according to template specifications. The system handles complex hierarchical component links, nested property references, time series attributes, and categorical values, generating properly formatted JSON or YAML output that matches each service's expected input structure while preserving all semantic relationships and data provenance.

6.10.3 Batch Submission and Polling

Users select multiple converted scenarios for batch submission to configured APIs, with the system handling sequential processing and progress tracking. For services requiring asynchronous processing like Sympheny, the module automatically manages job submission and status polling, displaying real-time updates on job progress and completion. Submissions include configurable retry logic, timeout handling, and error recovery, with detailed logging of request/response cycles and status codes for troubleshooting failed submissions.

6.10.4 Result Management and Persistence

All submission results are automatically saved to NextCloud in structured JSON format, organized by service name with timestamps and metadata including submission status, API responses, scenario IDs, and result URLs. Users can browse past results through a dedicated viewer showing submission history, success rates, and detailed response data. For Sympheny submissions, the system captures and displays multiple result URLs including scenario views, execution file locations, and dashboard links, enabling direct navigation to external analysis platforms. Results remain accessible across sessions and can be downloaded individually or in bulk for offline analysis, reporting, or integration with other tools.

7 PROJECT REFLECTION AND LEARNINGS

7.1 Platform implementation

The platform evolved considerably from its original conception to the final prototype. Early work explored the Azure Digital Twin Platform (ADTP) as a potential backbone, but evaluation revealed fundamental limitations for the Digicities use cases: ADTP's proprietary Digital Twin Definition Language (DTDL) lacked uptake outside the Microsoft ecosystem, configuration through the interface was not reproducible or scalable, and there was no support for geospatial visualisation. The decision to move to a GraphDB-based architecture with a prototype Streamlit application was pivotal, as it gave the project full control over the semantic model, allowed standard RDF/OWL tooling, and enabled the modular design that ultimately defined the platform.

A recurring lesson was the tension between generality and usability. The ontology needed to be flexible enough to accommodate diverse services (hydropower scheduling, battery simulation, energy dashboards, regional energy planning) without becoming so abstract that users could not understand or populate it. The attribute classification system (e.g. physical, cost, curve, categorical, geospatial, event) was design choice, since temporal characteristics could then be layered on top of any attribute category without creating parallel hierarchies.

The decision to implement nine distinct modules rather than a monolithic application allowed parallel development and independent testing, but it also required careful attention to data flow between modules. The scenario builder, for instance, depends on consistent ontology deployment from the ontology manager, valid instances from the replica builder, and correctly structured YAML from service registration. When any upstream module produced inconsistent output, downstream modules failed in ways that were not always immediately obvious. This experience argues strongly for automated integration testing in future iterations.

Authentication and access management through Keycloak proved essential for the multi-stakeholder environment. Workspace security addressed data sovereignty concerns raised during stakeholder consultations and aligns with the principle that the platform should orchestrate data exchange rather than centralise data custody.

7.2 Accommodating use cases

The application of the Digicities platform for the national use cases is detailed in the respective final reports of consortium partners. In the case of Switzerland, the two use cases placed fundamentally different demands on the platform, which was instructive for understanding its range of applicability. Swiss UC1 (operational decision-making) required tight integration between the semantic layers and machine learning workflows: time series data for demand and water inflow forecasting needed to be structured for LightGBM model training, weather forecast data had to be temporally aligned with prediction horizons, and the scheduling service required real-time data feeds alongside static configuration parameters. The platform's role here was primarily to organise and standardise the data that feeds an external analytical pipeline. The ontology's ability to distinguish between historic, live, and future time series and to reference external data sources through dynamic attributes proved well-suited to this pattern.

Swiss UC2 (energy planning) required a broader but less time-critical integration. The challenge was accommodating heterogeneous planning data (e.g. building stock characteristics, energy consumption profiles, geospatial boundaries, technology parameters) and making it available in a format that the regional planning API for the third-party service provider could consume. Here, the semantic data products and scenario builder were the most exercised modules: the workflow of loading data products, selecting component instances, building scenarios, applying assumptions, and submitting to an external API represents the platform's core value proposition for planning applications. The generation of sub-services for EV charging demand and solar façade potential illustrated how modular data products can compose into complex analytical workflows.

A practical finding from both use cases was that bulk data import (via Excel templates) was essential for initial platform population. Manually creating component instances through the replica builder interface is appropriate for small-scale testing or incremental additions, but the volumes of data involved in real use cases (e.g. hundreds of buildings, dozens of time series, multiple technology components) require batch workflows. The Excel import functionality, while functional, would benefit from more robust error handling and validation feedback in future versions.

The process of defining service requirements as YAML specifications worked well as a contract between the platform and external services. It formalised what had previously been implicit knowledge about what data a service needs, in what structure, and with what temporal characteristics. Service providers indicated that this formalisation alone has value in reducing ambiguity during use case integration.

7.3 Original objectives

The project set out with five primary objectives. This section reflects on the extent to which each was addressed.

Provide semantic data layers to support existing digital platforms and services. This objective was met. The ontology, data product structure, and scenario management workflow provide a functioning semantic layer that was demonstrated with two external services (the HPP scheduling controller and the regional planning API). The YAML-based service registration provides a reproducible mechanism for defining how the semantic layers interface with external platforms.

Enable the projection of energy demands to support decision-making. This was addressed through UC1, where LightGBM-based demand and inflow forecasting models were trained on data organised through the platform's structures. The forecasting models consistently outperformed baseline approaches and enabled automated scheduling decisions that reduced peak demand. The battery sizing simulations further demonstrated how the platform's data management supports systematic evaluation of technology options for decision-making.

Implement an architecture that helps organisations achieve secure data exchange. The Keycloak-based authentication, workspace isolation, and NextCloud storage provide a secure foundation for multi-stakeholder data exchange. The TrustRelay middleware for data sharing agreements was configured but not integrated into the final platform, leaving this as an area for future work. The workspace-based architecture supports evolution toward fully federated storage consistent with IDSA data space principles.

Use the data architecture to evaluate renewable energy integration and energy efficiency measures. This was partially addressed. Swiss UC1 evaluated renewable energy resource optimisation (hydropower scheduling and solar self-consumption with battery storage) and produced quantitative results. Swiss UC2 prepared the infrastructure for evaluating energy planning scenarios but did not complete a full evaluation cycle with quantified energy impact metrics within the project timeline.

Investigate new business opportunities to sustain the platform. The stakeholder assessment identified potential value propositions for different actors in the value chain. Digital service providers benefit from reduced integration effort and standardised inputs, while end users value data governance and traceability. However formal business model was not developed; however, releasing the full software stack as open-source is currently being considered. The service provider feedback suggests that the platform's value as middleware between data sources and analytical services could form the basis of a sustainable offering, particularly if combined with a growing catalogue of ready-to-use semantic data products.

7.4 Opportunities for future research

Several lines of future research emerge from the project, several of which would be significantly enabled by the consortium's consideration of releasing the full software stack as open source. An open-source release would lower the barrier to adoption for research groups and public-sector organisations, enable community-driven improvements to tooling and ingestion methods, and allow independent validation and extension of the platform's capabilities across a wider range of use cases and geographies. While this approach would preclude commercial licensing of the platform software itself, it would shift the value proposition toward services built on top of the platform and align with the open-source models that have proven effective for comparable semantic infrastructure (e.g., GraphDB's community edition, Apache Jena, Protégé).

Beyond the open-source opportunity, several technical research directions emerge. First, advanced semantic reasoning over the ontology's taxonomic hierarchies and external mappings remains largely unexploited. The current platform uses the ontology primarily for structuring and validating data; more sophisticated reasoning, such as automated inference of compatible data substitutions, consistency checking across scenario variants, or AI-assisted ontology quality assurance, could substantially increase the platform's value for complex planning studies.

Second, the federated architecture that the workspace design anticipates has not been fully realised. Moving from centralised GraphDB and NextCloud instances to a model where users connect their own triple stores and cloud storage through authenticated federation would address the data sovereignty concerns that stakeholders consistently raised. This requires research into federated SPARQL query execution across distributed endpoints, conflict resolution in ontology versioning, and governance frameworks for shared ontology extensions. An open-source codebase would make it considerably easier for organisations to deploy their own platform instances and participate in such federated arrangements on their own infrastructure.

Third, the integration of machine learning into the platform's core functionality presents opportunities. Automated data quality assessment, ML-assisted ontology mapping, transfer learning across similar use cases (e.g., applying demand forecasting models trained for one utility to another with limited local data), and automated feature engineering from semantic metadata are all areas where the combination of structured semantic data and ML techniques could yield practical improvements. Community contributions to these capabilities would be a natural benefit of open-source development, where researchers working on adjacent problems could contribute specialised modules.

Fourth, the semantic data product concept could be extended to support provenance-aware data marketplaces. The current structure already provides the metadata needed for discovery, interpretation, and ingestion; adding standardised licensing, usage tracking, and quality certification would enable commercial data exchange consistent with the European Data Act and GAIA-X principles. Notably, open-sourcing the platform would not prevent commercial exchange of data products themselves, as the value of curated, validated energy datasets is distinct from the value of the software that manages them.

Finally, the platform's applicability to more complex, multi-sector planning studies would test whether the ontology's flexible extension mechanism scales to genuinely cross-domain applications. Projects such as SWEET CoSi and REFORMERS provide immediate opportunities to explore this, while the NEST demonstrator at Empa offers a controlled environment for validating real-time data integration and digital twin synchronisation capabilities that were out of scope in the current project.

8 CONCLUSION

The Digicities platform demonstrates that a modular, standards-based architecture can provide a practical environment for managing semantic energy data across multiple stakeholders and use cases. The service-driven ontology design proved effective at reducing the adoption barrier associated with complex domain standards (CIM, SAREF, CGMES) by allowing developers to define only the components and attributes their services require, while preserving interoperability through on-demand mapping. The semantic data product structure provided a standardised publication and ingestion mechanism that eliminated ambiguity in data exchange. Workspace isolation through Key cloak addressed data sovereignty requirements and positions the architecture for evolution toward fully federated deployment where organisations host their own infrastructure. The nine-module design enabled independent development and testing but underscored the need for automated integration testing, as inconsistencies between upstream modules (ontology deployment, instance creation, service registration) propagated to downstream workflows in ways that were not always immediately apparent.

The use cases validated different aspects of the architecture: the operational decision-making use case confirmed that the platform's semantic structures and temporal data handling can support ML-driven control pipelines with external scheduling services, while the energy planning use case demonstrated the end-to-end workflow from data product creation through scenario building to external API submission (use-case-specific results are detailed in the respective national final reports). The consortium is considering an open-source release of the full software stack, which would shift the value proposition from platform licensing to data products, integration services, and domain expertise, while enabling community-driven refinement of the tooling and broader accumulation of the case studies that stakeholders identified as prerequisites for adoption. The technical architecture is in place; sustained impact depends on expanding the semantic data product catalogue, establishing community governance for ontology development, and applying the platform in progressively more complex real-world studies.

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