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A use case driven design approach of an energy data exchange platform

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Abstract: The current digitalization of energy systems, particularly in urban contexts, lags behind the requirements set by urban energy system modelling, energy management, the development of digital twins, and other data-driven services. Additionally, existing energy data lacks standardized formats and coherence, hindering its full utilization. To address this challenge, this paper introduces a use case-driven design approach tailored to reflect the requirements for data integration and privacy set by city stakeholders. The objective is to design a data exchange platform (DEP) capable of serving a diverse range of use cases. This platform will facilitate the integrated utilization of energy data in energy management systems, digital twin applications, and other activities aimed at extracting valuable insights. These efforts are specifically designed to support decision-making processes of public stakeholders, private investors, and service providers. Consequently, the platform holds potential to attract additional investments in both the clean energy transition and the digitalization of energy infrastructure.

Keywords: Urban Energy System, Data Exchange Platform, Data Architecture, Digitalization

1 Introduction

The European transition strategy emphasizes the interdependence between the digital and green transitions. The concept of “twin transitions” is presented in the Joint Research Centre publication “Towards a green and digital future”, and according to the EU, digitalization can support the energy transition at different levels [1]. Specifically, digitalization can support the green transition in the following ways: real-time knowledge can be provided through monitoring infrastructure to enhance energy management systems, energy efficiency can be improved through simulation and energy demand projections, and leveraging digital platforms helps managing the growing complexity of energy systems [1]. Furthermore, the digitalization of energy data, e.g., monitoring data, structural building data, infrastructure data, or energy potentials, is emphasized as a key enabler for urban energy system modeling and the development of urban decarbonization strategies [2]. Moreover, a structured representation of such data within commonly used semantic frameworks can enhance the usability of such data for urban energy system modeling. Although today's administrations produce manifold data on energy consumption, privacy restrictions often prevent the public disclosure of this data. As a result, stakeholders involved in the energy transition are unable to leverage this valuable information [3].

The ERA-Net project DIGICITIES will showcase a data exchange platform (DEP) designed to facilitate the digitalization and sharing of energy data. It aims to establish transparent pathways to represent and share data particularly for purposes such as energy demand forecasting and energy consumption monitoring. The DEP will rely on linked semantic data ("digital layers") to support existing digital platforms and services [4]. The DEP structured built around use cases for energy demand modeling, energy consumption monitoring and energy supply system optimization from Austria and Switzerland. This contribution presents the first Austrian use case (AUC1) and its requirements for the DEP, revolving around the representation of monitoring data, the validation of a simulator developed for simulating building energy performance of AUC1, and the exposure of relevant data to stakeholders of the use case and practitioners in urban energy system modeling practitioners. The following sections offer a concise literature review on existing data exchange architectures for urban enegry data, as well as a short description of the DEP developed within DIGICITIES and the use case AUC1 and its integration into the DEP including the its utilisation for validating the building energy modeling simulator..

1.1 Data architectures and management for urban energy modeling

Data architectures at the building scale can be described as a combination of different layers or functional requirements. In a review, Mendoza-Pitti *et al.* identify eight functional requirements for energy data architectures in buildings: (1) the data sources layer, (2) the networking layer (3) the data cleaning and preprocessing layer (4) the data storage layer, (5) the integration layers, (6) the data analysis layer, (7) the application and presentation layer, and (8) the decision-maker layer [5]. Not all existing architectures include every functional requirement. For example, simplified models such as the BEMS (Building Energy Management System) architecture developed by Ruiz *et al.* can be summarised in three different layers [6]: the data acquisition and transportation layer (including data sources and formats), the data analysis and decision-making layer (processing data based on data mining and machine learning techniques [7] and enabling the energy demand prediction for the building), and the control unit layer (aiming at managing the daily operation plan based on data analysis results). Moreover, Marinakis proposes an iterative process to build up a data architecture for buildings that starts with the setup of the infrastructure to collect data (energy, governance, weather, and climate data). A governance layer then operates as a mediator between data users and providers. The data are gathered with interoperability service modules such as OMA NGSI 9/10 FIWARE and are enriched, cleaned, and formatted [8]. The third layer is the processing layer, which encompasses machine learning processes to manage the collected data. Finally, the analytics layer provides a toolbox to optimize the use of building operations.

Data exchange architectures that aim to support building energy management and urban energy system modeling require not only functional layers but also non-functional characteristics. The review conducted by Mendoza-Pitti *et al.* highlights five non-functional requirements: scalability, processing, interoperability, heterogeneity, and security. Although most of the existing architectures are designed to be adapted to an increasing number of data and to different languages or systems, only few architectures integrate a fault tolerance framework or a dedicated security and privacy layer [5]. Marinakis stresses the need to add a cyber security and data privacy layer to all the different existing layers of a building data architecture [9]. These security layers are also critical when scaling the data architecture to the city level. Osman proposes a smart city architecture including two security layers: one after the data collection layer, and the second before the end user's data visualization [10].

Data ontologies and schemas can leverage energy data to allow the implementation of integrated services such as demand forecasting, energy management, decision-making support, or predictive maintenance across use case domains [11]. These services require data on various levels of spatial and temporal granularity. For instance, city-level policy-making may utilize annual data on spatially aggregated energy demand sectors [12], while time series energy demand prediction on the building level [3] and district scale energy system modeling [13] require more fine-grained data on the spatial and temporal scales. Different levels of granularity can also be attributed to the aspects of energy demand and supply themselves, as urban energy modeling frameworks operate on varying levels of detail concerning energy supply technology representations [2]. Currently, data models for urban energy issues integrate varying levels of abstraction and granularity, while no single data model allows a representation of all levels of granularity [14].

1.2 Challenges

The sharing of building energy data, including information on thermal properties of building envelopes, energy supply systems, monitoring data, usage schedules, and simulation data is often hindered by challenges of heterogeneity in its semantic representation and administrative complexities. In the case of buildings, semantic interoperability of data schemas is often limited, as outlined by Pritoni *et al.*, who provide a review of metadata schemas on the building level and their interoperability [15]. The work concludes with recommendations for the implementation of centralized databases and search engines to make existing ontologies more accessible and comparable. Furthermore, the authors advocate for the harmonization and standardization of data schemas across stakeholder groups, as the interoperability between the investigated schemas was found to be insufficient. Another study describes digitalization and semantic interoperability as inconsistent across different spatial scales, e.g., the building to city level [16].

Data quality is also an essential criterion for accurate energy modeling and data sharing. Faulty sensors or Internet of Things (IoT) systems can cause compromised data sets that require cleaning and thorough documentation before utilization. [17]. There have also been calls for improved transparency and documentation practices related to data integration [18]. The relevance of data quality is further underlined in relation to trust between entities sharing IoT data [19].

The DIGICITIES DEP aims to tackle these challenges by establishing a platform that uses semantically interoperable data schemas for urban energy data and, where necessary, provides manual links. Additionally, standardized data cleaning scripts and quality checks of gathered data are intended to be developed and integrated into the platform.

1.3 Technical data exchange platform architecture

The following section describes the technical specification of the DEP that has so far been agreed upon within the project consortium as depicted in figure 1.

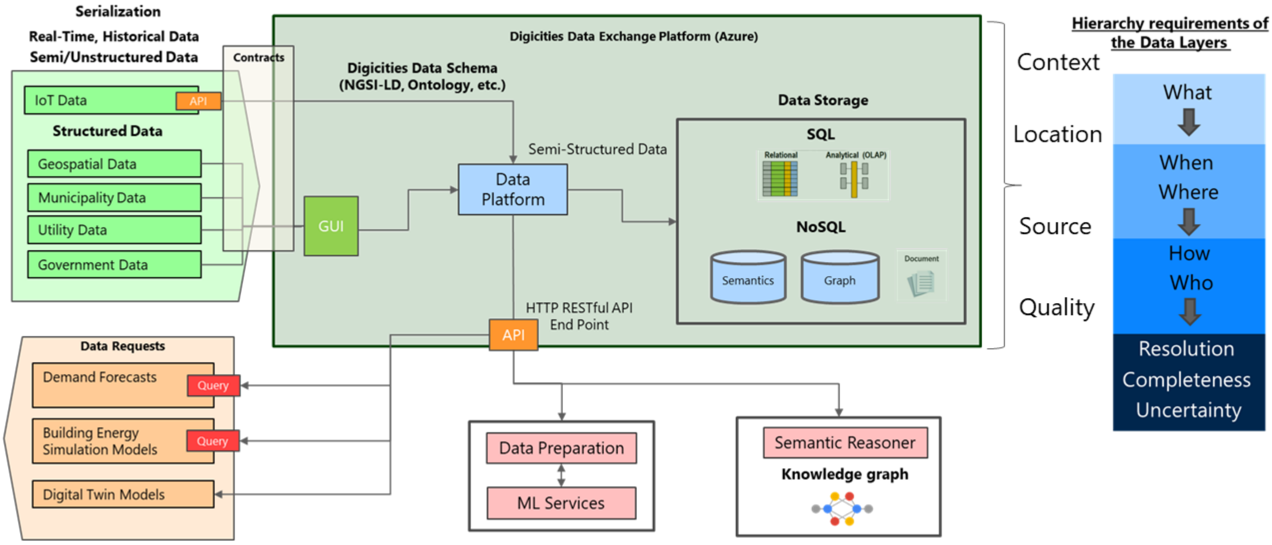

Figure 1. *Conceived platform architecture overview*

1.4 Outline of this contribution

The review of the literature and recent projects has revealed a widespread lack of standardization in urban energy modeling data. This paper explores the requirements of a DEP to enable structured data representation which – if accessible – supports energy modeling activities. This contribution focuses on building data; however, the concepts explored are scalable. The herein developed and presented requirements and functionalities of the DEP aim to meet the needs of one use case and will be applied to further use cases to prove the concept and to utilize the DEP. The broader project objectives are listed below [4]:

- Provide a transparent source of semantically tagged data ("digital layers") to support existing digital platforms and services that integrate urban energy data from various layers to support urban-scale energy modeling and monitoring.
- Facilitate the projection/forecasting of urban energy demands to assist cities in reaching their energy and climate objectives through informed decision-making.
- Integrate monitoring data and simulation results into a common data platform that serves the needs of identified stakeholders and allows the adaptation of building operation strategies.
- Implement a data architecture using best available practices to preserve sovereignty and privacy.
- Derive common data cleaning routines from the considered use cases that can be translated into data quality requirements for data contributions.
- Demonstrate the platform's functionality on the basis of the considered use cases.
- Support research initiatives by providing access to comprehensive energy data for analysis and innovation in energy technologies and systems.

With these objectives in mind, this paper deals with one Austrian use case and describes its requirements regarding data exchange for energy modeling and demand forecasts of buildings at an urban scale. The paper describes the integration of monitoring and simulation data from AUC1 within the DEP's multi digital layer concept to allow for the calibration and validation of simulation models and to enable structured queries for monitored and simulated time series data for the buildings' energy demand and retrospective energy consumption. This paper also explores the necessary transformations required to prepare data from such use cases to be used within the DEP. Specifically, observed data quality issues are documented, and related data cleaning routines are derived that will shape the overall requirements on data quality for the platform.

2 Austrian use case 1

The following section introduces AUC1 and its implementation within the DEP. AUC1 deals with the monitoring and evaluation of a zero-energy building (ZEB) of Neue Mittelschule (NMS) Enkplatz, a middle school in Vienna that was completed in 2019. The energy concept of the ZEB of NMS Enkplatz covered in AUC1 includes a mix of different onsite renewable energy supply sources, comprising a solar thermal system, a PV system with an overall power of 67 kW, and a 2-stage heat pump supplied by shallow geothermal energy. Besides, the ZEB is connected to the public electric grid, as well as to the district heating network, which on the one hand functions as a backup for the heating supply, and on the other hand receives excess heat from the solar thermal system, especially during summer. The monitoring data to be represented in the DEP comprises meter data from the mentioned energy supply units as well as sub-meters for individual heat consumption zones and distribution systems. The building energy system of the ZEB aims to achieve an annual net-zero energy balance [17]. Furthermore, the heat pump works for cooling (in summer) and heating (winter) to compensate the heat loss of the ground water. For optimal indoor air quality, a ventilation system with heating register is used for the gyms [20]. Figure 2 illustrates the energy concept of the building. The building features an extensive energy monitoring system that was implemented throughout the previous EU project Smarter Together [21], which demonstrated the transfer of raw meter data to the urban data platform of Vienna. Figure 2 provides an overview of the energy supply system covering the energy demand of NMS Enkplatz.

The use case is in an advanced stage and provides clear insights into the current practice of data gathering, processing, and further application. The representation of AUC1 within the DEP aims to serve as the foundation for developing data integration pipelines and specifying requirements for data quality and semantic mapping within the DEP. The DEP aims to support AUC1 regarding the access to data cleaning routines, calibrated modeling data, and energy demand forecasts. Such applications are envisioned to improve the utilization of local energy resources and flexibility options to achieve a zero-energy balance in operation. Furthermore, the disclosure of energy data of such a building is conceived to support urban energy system modeling, as energy data for public service buildings like schools can be difficult to obtain. Thus, it provides a use case for demonstrating and developing the DEP.

3 Implementation of AUC1 within the data exchange platform

The following section describes the requirements set forth towards the DEP by AUC1 and the progress made in implementing these requirements. The process of the implementation of AUC1 in the DEP addresses several steps covering: collection/provision

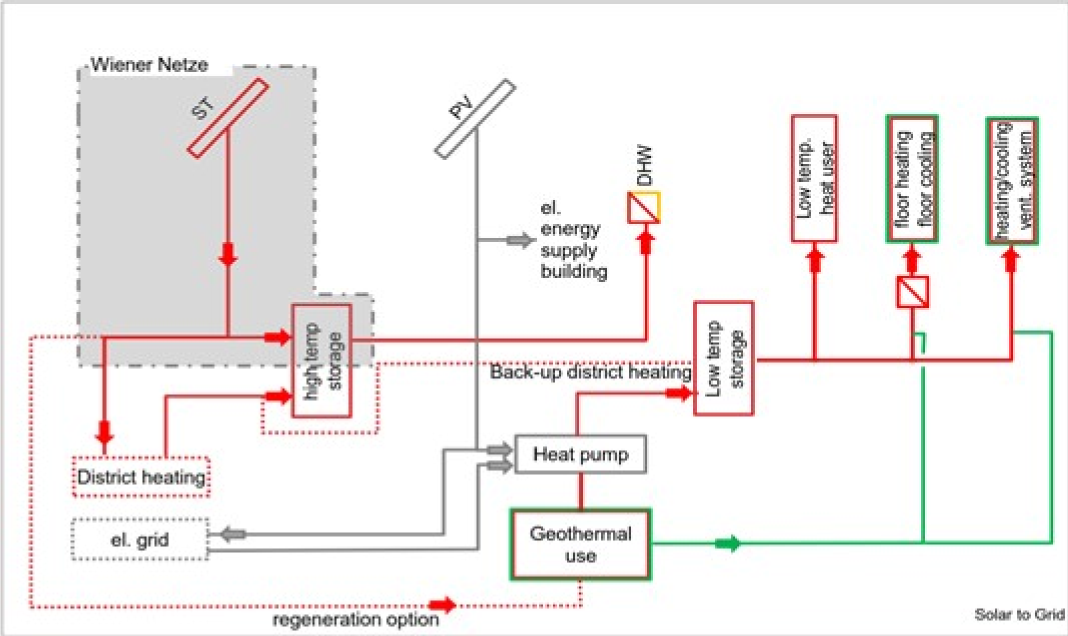

Figure 2. *Simplified flowchart of the energy concept of Austrian use case 1 (AUC1), the zero-energy building (ZEB) of Neue Mittelschule (NMS) Enkplatz, a middle school in Vienna, Austria.*

of raw monitoring data, cleaning the data using a semi-standardised cleaning routine, data visualisation, data mapping to generate a building data ontology using a Brick model resulting in a knowledge graph that offers a semantic linking of the building data, provision of cleaned data for validation of the building simulator that finally provides a validated tool to fulfil the requirements of city need owner in terms energy demand forecasting and optimisation of building operation. The process of data cleaning and validation procedures that can be carried out on the platform, and the semantic linking of data layers to facilitate the calibration of simulation models and dissemination of modeling results and monitoring data. Following the use case driven design approach, the findings of the implementation of AUC1 in the DEP serve as the foundation for the functionalities of the DEP to be provided for further use cases.

3.1 Collection and cleaning of energy monitoring data

The first central function of the DEP regarding AUC1 involves the collection of monitoring data from various energy meters and the evaluation of the building's energy balance. To verify the ambition of achieving an annual zero energy balance, data gathered by the monitoring system needs to be employed to generate relevant Key Performance Indicators (KPIs) for evaluation, and subsequently be exposed to the relevant stakeholders (building owners, building operators, utilities and researchers).

The identification of monitoring infrastructure, e.g., sensors, meters and the logistics for data acquisition, is a fundamental first step towards the development of the DEP. A total of 11 electricity meters and 21 heat meters are installed on site at AUC1 to monitor raw building energy demand and supply data with a sampling frequency 15 minutes. The monitoring time cover a full year of building operation. Relying on this monitoring infrastructure, the following data can be automatically collected: the thermal energy consumption (partially diaggregated by rooms and floors), the electric energy consumption, the thermal energy generated by the solar thermal collectors and the heat pumps, as well as the nominal power and electricity production of PV panels

[17], [22], [23]. The energy meter data are currently communicated to AIT as raw time series batch data, which necessitates data processing and cleaning steps.

The raw data of AUC1 were subsequently subjected to cleaning routines, which were standardised as far as possible to serve as the basis of automated cleaning and data quality checks in the DEP. The cleaning involved an initial step tailored to the AUC1 data in which different received time series batches had to be reconciled due to non-uniform datetime indices, different time zone encodings and time overlaps, the latter of which were resolved by taking the maximum if multiple values were specified at some datetime. The cleaning continued with the following generalised steps, aimed at providing maximally reliable energy (not power) values. First, all zero values were set to "missing" as the sensors recorded energies (cumulative data) with recording starting at zero and a constant value indicating the absence of change. Next, errors in the order of magnitude of a value – caused e.g. by a misplaced decimal point in the raw data – were identified by comparison to neighboring values (requiring ratios close to 100, 1000 etc.) and remedied. Subsequently, stark outliers were removed, defined as deviations from a time series's median by more than 10 times the difference between the 90% and 10% percentiles. Then, all time series were converted from energy to power by differencing, after unbounded forward-filling of the energy values to enable a later recovery of energy values by integration. In the representation as power values, pairs of a negative followed by a positive value were identified (by requiring similar absolute values and temporal proximity) and then leveled out. Further, negative values preceded by a sharp but non-instantaneous rise of similar magnitude (e.g. over one day) were identified and leveled out. Finally, the remaining negative power values were set to zero, and for a return to energy values an integration was carried out. Figure 3 provides exemplary results for the outlier removal and filling of gaps in time series data.

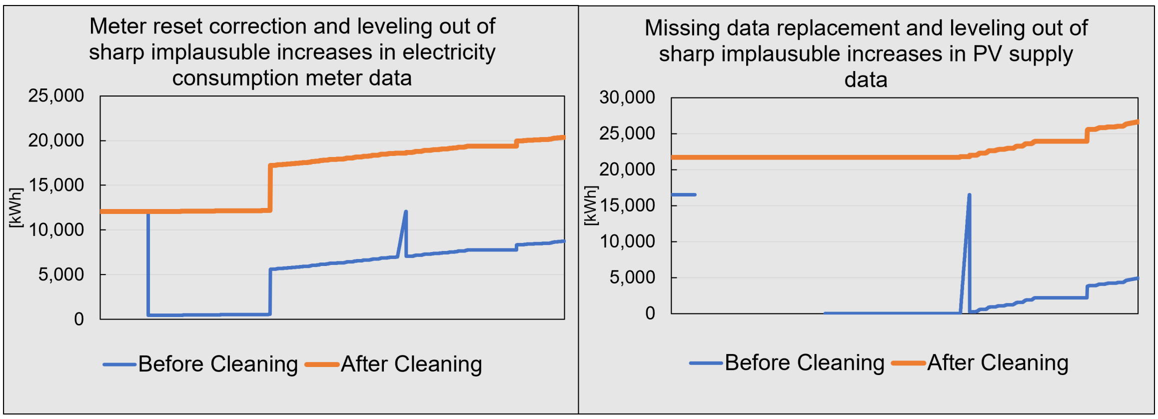

Figure 3. *Example results for the cleaning of energy meter data. The plots show time periods of several weeks (the time axes were removed due to data privacy).*

The handling and data cleaning of AUC1 allowed the compilation of a first set of requirements that is to be aligned and verified with use cases. The quality requirements for time series data derived from AUC1 comprise checks and cleaning for:

- Missing entries
- Overlapping and conflicting entries
- Faulty measurements (e.g., unrealistic peaks or valleys)
- Inconsistent time labeling
- Sensor and meter changes

3.2 Validation of ZEB Simulator

To achieve a net-zero energy balance for AUC1, the operational scheme of the energy supply system needs to be optimized, employing energy demand forecasts and suggestions for operational improvements to optimally utilize the local flexibility options. For this purpose, a simulator of the ZEB of NMS Enkplatz is developed, using the building simulation software IDA-ICE [24]. The simulator is being validated using the cleaned monitoring data representing different building zones and energy consumption and provision. The validation process confirms that the model is predictive under the specified conditions of the measured building energy monitoring data and thus the developed simulator is valid for its intended use. However, the validation process also shows that not all use characteristics of the building, i.e., use schedules of rooms and the control strategy are yet represented correctly in the simulator. The intended use of the simulator covers optimisation of building energy performance under defined operation conditions and Short-term forecasting of building energy performance (including demand forecasting). Furthermore, the simulator can support the planning process of similar buildings to achieve optimal building energy performance under the given operational limits and conditions. The energy demand forecasts derived from the simulator are mapped onto the same representation of the building within the DIGICITIES knowledge graph, described in section 3.3. The DEP therefore provides a structured and reliable source of information for building energy model calibration. Besides benefiting the operator and owner of the school at Enkplatz by providing optimized operation strategies, facilitating the access of building energy data from both measurements and simulations via the DEP with the DIGICITIES knowledge graph will be a relevant contribution to improve data driven urban energy services, as access to energy data is a widely acknowledged issue in research on urban energy systems [3].

3.3 Data access/queries and linked semantic data layers

As the central goal of the DEP is to facilitate data exchange between stakeholders in urban energy applications, the common semantic data framework in DIGICITIES – the DIGICITIES knowledge graph – serves as the main interaction point to access and query monitoring and simulation data from AUC1. The structure of the DIGICITIES knowledge graph in the case of AUC1 is described in the following.

Spatial aggregation of energy data was identified as a requirement for urban energy DEPs as it can enable sufficient anonymization of data to be exposed on open DEPs and can facilitate the application of machine learning methods. This functionality can be supported by interlinked semantic layers that cover energy data at different spatial scales. The DIGICITIES knowledge graph therefore integrates the H3 Hexagonal Hierarchical Geospatial Indexing System (H3) [25] to represent spatially-aggregated data above the building level. Based on literature review and the consideration of the given use cases, the following concept for the semantic linking of data was developed.

The measured data from AUC1 are mapped to a representation of the building using the building data ontology BRICK [11]. The main concepts that are employed in the BRICK model of AUC1 are energy zones, HVAC zones, HVAC equipment, electrical meter, thermal energy meter, PV panel, and solar thermal collectors. Thus, the DEP provides spatial context to the developed BRICK model by integrating it into the underlying H3 indexing system. The BRICK model will be extended to differentiate between measured and simulated data.

Combined with the quality check, cleaning routines, anonymization and data management features of the DEP described in sections 3.1 and 1.3, the DIGICITIES knowledge graph allows data uploaded to the DEP to be queryable to provide structured information on monitoring data and energy demand forecasts from calibrated simulators. The next steps comprise the integration of data on thermal properties of the building and energy supply assets into the knowledge graph. Figure 4 provides an overview of the integration of AUC1 within the DEP and the related queries to be provided. While currently not all of the following queries can be supplied with data, example queries can involve accessing the following information for specific buildings (like AUC1), or building clusters:

- Annual energy balance by energy carrier and end use category [kWh/a]
- Annual cumulative energy balance [kWh/a]
- Heating and cooling demand forecast for the next 48 hours hourly [kWh/h]
- Electricity demand forecast for next 48 hours hourly [kWh/h]
- Expected PV production forecast for next 48 hours hourly [kWh/h]
- Thermal storage charging and discharging suggestion next 48 hours hourly [kWh/h]
- Specific space heating demand resulting from modeling or monitoring [kWh/m²a]
- Annual domestic hot water demand [kWh/a]
- Annual modeled peak demand and monitored peak load for electricity, heating and cooling [kW]
- Annual supply ratio [%]
- Thermal properties of building envelope

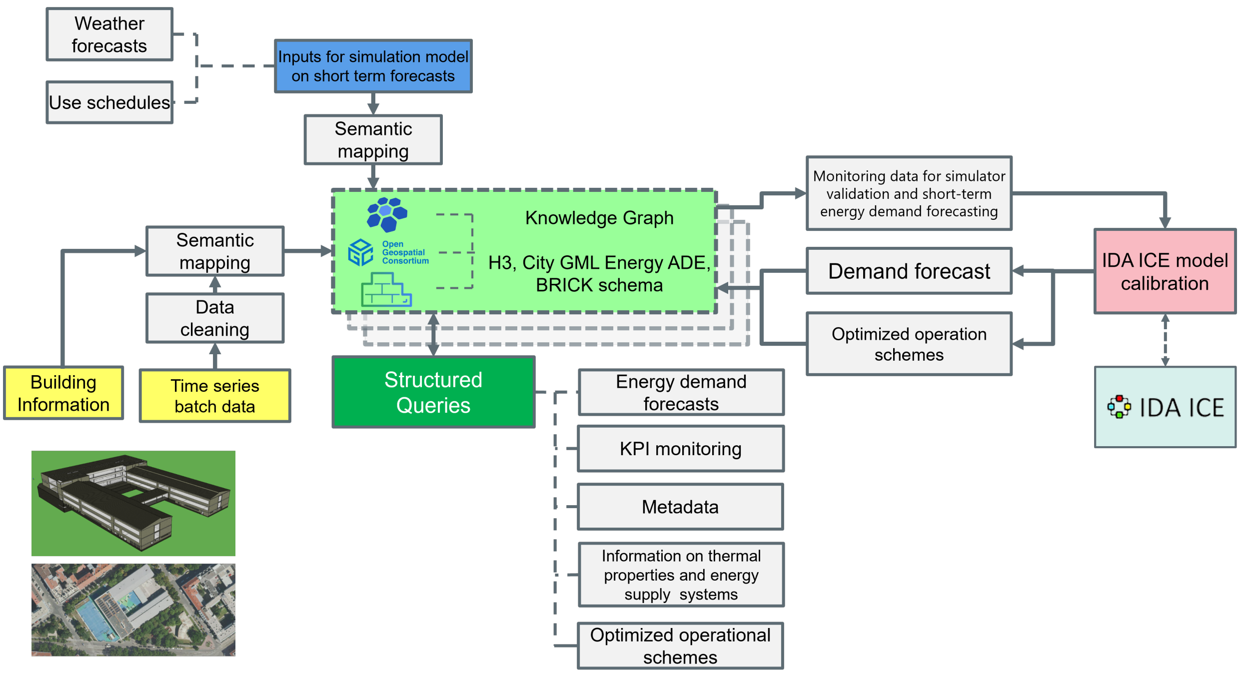

Figure 4. *Representation of AUC1 in DEP*

4 Benefits of the DEP for AUC1 and requirements towards the platform (discussion)

This section summarizes the implementation of AUC1 within the DEP and details the achieved integration within the DIGICITIES knowledge graph. Currently, workflows to establish data transfer, storage solutions and data management practices (as applied during the development phase) are described alongside formulated visions for a final implementation of data sharing practices in the DEP.

The requirements of data management extracted from AUC1 and urban energy modeling show that data need to be represented on different aggregation layers, on different levels of detail and across different domains. The semantic mapping and subsequent representation of building energy data using commonly agreed data schemas and ontologies facilitates the access and use of building energy data for services like energy demand forecasting for building operators and the provision of building information for urban energy modeling. Additionally, the organization of building energy data using established ontologies facilitates data interoperability across different domains and physical scales. This is a critical feature for urban energy modeling and the sharing of energy data as energy needs to be collected, processed and represented at different spatial and temporal scales. AUC1 is an example for the linking of semantic models across these spatial scales. The developed BRICK model can be linked to other semantic models like a CityGML model and the H3 hexagon representation to allow the integration of data through higher levels of abstraction. This is planned in the following implementation steps of the project.

The technical transfer of data onto the platform has been established in a manual process within AUC1, as many of the defining features, the data cleaning routines, the simulator development and calibration and the query definitions had been under development before the technical infrastructure of the DEP had been established within the project. This means that data cleaning and quality checks have been performed manually outside the platform. The next steps comprise the integration of the cleaning scripts, quality checks and queries into the data upload and sharing processes of the platform.

The review of AUC1 and its implementation on the DEP resulted in the following specification of platform requirements to be implemented in the final versions of the DEP to to enhance the management of meter and sensor data. The goal is to deliver a transferable way of building energy data sharing within an open data platform. Specifically, this entails:

- Mapping of data points to the DIGICITIES DEP and employed data ontologies, e.g., BRICK [26]
- Applying standardized data quality checks and cleaning processes based on the experiences made in section 3.1
- Establishing data sharing contracts to manage data requests of different users
- Providing standardized queries for each represented energy asset (energy infrastructure or buildings etc.) data model within the DIGICITIES knowledge graph

4.1 Outlook for platform application in urban energy transition

DEPs like the one in DIGICITIES can be a crucial enabler for the development of urban energy models across different spatial scales. Combined with robust data sharing policies, a validated approach towards data quality checks and the semantic mapping of building information and energy data can incentivise the sharing of individual building data, as showcased in AUC1, and city scale information on buildings and energy demand. Especially the integration of city-scale building registry data in combination with the CityGML Energy ADE [27] can be the foundation for advanced urban energy system modeling, as exemplified in [28]. The integration of such registries within the

the semantic framework of the DEP is entailed within the next steps of the DIGICITIES project, covering the Swiss use cases of the project.

Additionally, the increased provision of calibrated model data from individual examples like the school building in AUC1 can provide valuable reference data to develop statistical building models for urban energy system modeling. If sufficiently many building operators provide their consumption data in that manner, models like [29] can be extended to include validated energy consumption models and improve the overall quality of urban energy system models.

5 Conclusion

A lack of data availability and poor data quality limit the potential of the application of building monitoring data in building simulation and optimization of energy supply system operation. The digitalisation of cities and urban energy systems will increase the quantity and quality of data. However, data producers and providers must adhere to standardized practices regarding data quality and cleaning, semantic representation and privacy related issues to ensure the data are interoperable across domains and use cases. This approach enables the data to serve further use cases like urban energy system modeling. Data exchange platforms like the one presented in this contribution can support data providers and users by providing semantic frameworks, data cleaning routines and quality checks. This is important for cross-cutting applications such as urban energy modeling and individual building operation support. Users and developers of urban energy system modeling tools will benefit from applications designed to work with linked data organised according to established ontologies and schemas. This paper explored the necessary features of a data exchange platform for hosting and sharing energy data at the building level, including monitoring data and simulation data. We conclude that the data exchange platform should have the following functionalities for such use cases:

- Standardised data cleaning routines and quality checks should be provided to ensure a certain level of data quality regarding time series data
- Data should be structured according to standardised data models to support interoperability
- Standardised queries should be provided to facilitate interactions with the platform
- The platform should contain real time indicators of system performance

The presented concept considers combining various data sources and streams to connect city stakeholders and support the advancement of the urban clean energy transition. AUC1 deals with the processing of building data relevant for the development of building level simulators and urban energy systems modeling and its representation in common data schemas like BRICK and CityGML to maximize interoperability. To support operational schemes for the zero-energy building in AUC1, a simulator is developed using the software IDA-ICE and energy demand projections generated by this simulator will be represented in the DEP to support the building operators. The implementation of AUC1 into the DEP structure led to the derivation of data cleaning routines and quality checks for time series data that can be transferred to other use cases that are to be represented on the DEP. While many of the developed cleaning methods can be applied to other datasets, not all of them transferable due to the individuality of errors in metering of energy consumption, which leaves room for further research. The semantic mapping of monitoring data onto the above mentioned data schemas supports interaction with the monitoring data for potential external users and for the calibration of the IDA-ICE simulator. Once calibrated, short-term energy demand projections provided by the simulator will further be represented on the data schemas to maximize their utility for the building operators.

Author contributions

Daniel Horak: Formulation of overarching research goals, preparation of the initial draft, revision
Lukas Lorenzen: Formulation of overarching research goals, presentation of the published work, review
Jan Kurzidim: Provision and application of data cleaning concepts, review
Ali Hainoun: Acquisition of financial support for the project leading to this publication.

Competing interests

The authors declare that they have no competing interests that could have appeared to influence the work reported in this paper.

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