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SEMI-AUTOMATED GENERATION OF METERING CONCEPTS AND SANKEY DIAGRAMS FOR TECHNICAL MONITORING USING KNOWLEDGE GRAPHS

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Summary

A metering concept is an important preparatory step for implementing Technical Monitoring of buildings (TMon), and is particularly relevant for energy monitoring, as it defines which and where meters are required. It is often supported by energy flow diagrams drawn as single-line schematics, which provide an overview of the main assets in the energy supply chain of a building and their connections. Based on these structural representations and the associated meter data, Sankey diagrams visualise the energy balance within defined system boundaries. This work proposes a graph-based workflow that uses a semantic representation of the systems to support the semi-automated derivation of metering concepts and the generation of consistent Sankey diagrams. The relevant energy-flow topology is represented as a knowledge graph. The workflow is demonstrated on a building energy system based on a water-source heat pump system with storage, distribution, and consumer groups. The resulting metering concepts are visualised as energy flow diagrams, while linked time-series data enable consistent energy aggregation and the generation of Sankey diagrams from the same underlying representation.

Keywords: Knowledge graphs, Semantic modelling, Metering concept, Energy flow diagram, Sankey diagram, Technical Monitoring

Field of application: Technical Monitoring, Building energy management, Digitalisation, Energy-efficient non-residential buildings

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1. Introduction

Technical Monitoring (TMon) of building performance is gaining importance in both the public and private sectors, as it enables the systematic identification of faults and energy-saving potentials in building operation and can thereby improve energy efficiency, cost-effectiveness, functionality, and indoor comfort. Its growing relevance is reflected in current standards and guidelines: energy management systems require the ongoing monitoring and measurement of energy performance (ISO, 2018), and technical monitoring has been established as a dedicated instrument for the quality assurance and operational optimisation of building energy systems (VDI, 2017; AMEV, 2025).

A prerequisite for TMon is a metering concept, which defines which meters are required and where they need to be placed in order to measure and balance the energy flows across the relevant system boundaries. In engineering practice, such concepts are derived manually from technical system schematics and documented as energy flow diagrams drawn as single-line schematics, which provide an overview of the main assets in the energy supply chain of a building and their connections, together with the meter locations. Standards such as EN 17267 structure the measurement scope into levels (DIN, 2020), and the AMEV Technical Monitoring recommendation specifies component-specific measurement requirements (AMEV, 2025). However, applying these requirements to a specific building energy system still requires interpretation of the system topology to determine the corresponding meter locations. The same effort recurs downstream: based on these structural representations and the associated meter data, Sankey diagrams visualise the energy balance and help to identify losses and optimisation potentials (Schmidt, 2008; Soundararajan et al., 2014; Liu and Mancarella, 2016), and this consistency between the schematic, the metering concept, and the measured data is difficult to maintain by hand.

Semantic models offer a way to reduce this effort by describing the system in a machine-interpretable form. Ontologies such as Brick Schema (Balaji et al., 2016) and ASHRAE Standard 223P (ASHRAE Standard 223P Community, 2026) provide structured descriptions of building assets, their relationships, and associated data points. When these descriptions are instantiated as a knowledge graph, the system structure and its measurement data are represented in a consistent and queryable form (W3C, 2014; Hogan et al., 2021; Lygerakis et al., 2022). Such a representation alone, however, does not determine which energy flows should be measured; an additional method is required to derive the required meters and their locations from the system topology.

This paper proposes a graph-based workflow that derives a metering concept from a knowledge graph of the building energy system and generates a consistent Sankey diagram from the same representation. The graph encodes the equipment and the directed energy flows between them; a rule-based Graph Engine queries it for the relevant system structures and assigns the required meters and their locations. The contributions are threefold: (i) a specification of the semantic information required by the proposed method for automated meter placement; (ii) three cumulative metering scopes, adapted from the level scheme of EN 17267, together with a corresponding set of executable graph-placement rules that translate the component-specific measurement requirements of AMEV into meter placements on the graph; and (iii) an end-to-end demonstration in which the metering concept, the measured data, and the resulting Sankey diagram remain linked in the same knowledge graph, evaluated on real building energy systems.

2. Method

The workflow starts from an energy flow diagram of the system — the single-line view on which the metering concept is defined, comprising the components, their energy flows, and the balancing boundaries rather than the full hydraulic detail. This diagram is modelled in the DiMASH-App, an AI-based tool for digitising technical building system diagrams into semantic models (Gölzhäuser et al., 2025), and exported using the TBSys (Technical Building System) ontology, which builds on ASHRAE Standard 223P and Brick Schema (Gölzhäuser et al., 2025). The result is a knowledge graph that encodes the equipment, the directed energy flows between them, and the balancing boundaries between functional groups. In the following, this knowledge graph is referred to simply as the graph. Its production is not part of the present work.

The workflow is summarised in Figure 1. The graph is the input to a rule-based Graph Engine that interprets it in four steps: it identifies the relevant system structures, places the required meters on the corresponding energy flows, assigns each meter to a measurement scope (Base, Medium, or High), and writes the resulting metering concept back into the graph. Measured time-series are then linked to the placed meters, and a Sankey diagram is generated from the same graph. Only the modelling of the energy flow diagram and the review of the proposed concept require the engineer; the interpretation steps run automatically, so the workflow is *semi-automated*. The following subsections detail the modelling requirements, the rule-based derivation of the metering concept, and the data binding and Sankey generation.

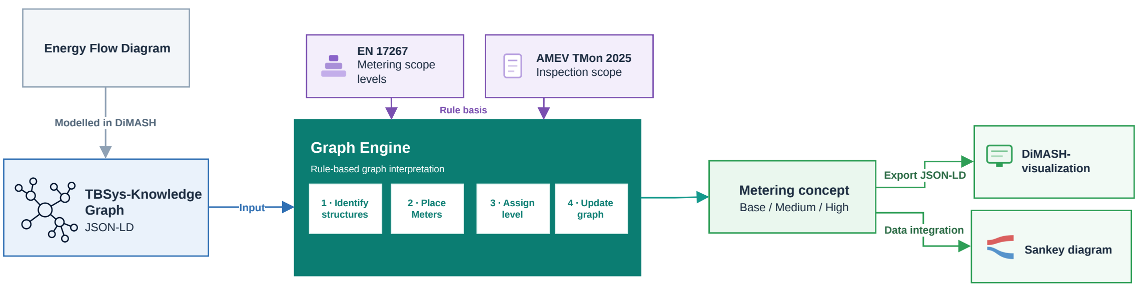


Fig. 1: Overview of the graph-based workflow for deriving the metering concept and generating Sankey diagrams.

2.1 Modelling requirements

The graph represents the relevant equipment, their connection points, the directed connections between them, and the transported media using concepts from ASHRAE Standard 223P (ASHRAE Standard 223P Community, 2026) and Brick Schema (Balaji et al., 2016), extended by TBSys (Gölzhäuser et al., 2025). The Graph Engine queries it for the recurring structures that determine meter placement: the input and output connections of energy-conversion equipment, the branches of distribution components, the charging and discharging connections of storage, heat-transfer interfaces, and consumer supply paths.

To support this rule-based derivation, the input graph must provide the semantic information required for the metering concept to be derived. Table 1 summarises what the Graph Engine requires and the ontology constructs through which it is represented. Most requirements are topological; technical properties are needed only where a component-specific rule evaluates a capacity threshold.

Tab. 1: Required semantic information and ontology representation for metering-concept derivation.

Modelling requirement	**Information required by the Graph Engine**	**Ontology representation**
Equipment classification	Each relevant physical component and its specific equipment type, including energy generators, heat exchangers, storage units, distributors, and consumers.	Instance of `s223:Equipment` and an appropriate TBSys or Brick class, such as `brick:Heat_Exchanger`, `brick:Storage_Tank`, or `tbsys:Distributor`.
Connectivity and direction	The connections between components, their connection points, and the upstream and downstream orientation of each flow path.	`s223:Connection` and `s223:ConnectionPoint`, linked through `s223:cnx`. Directional relations such as `s223:connectsFrom` and `s223:connectsTo` may be asserted directly or obtained through inference.
Medium and flow type	The physical medium transported by each connection and, where required, its energetic function within the system.	`s223:hasMedium` with the corresponding medium, such as water, air, refrigerant, gas, or electricity. Heating- and cooling-related flow classifications are represented through the corresponding TBSys constructs.
Functional grouping and roles	The assignment of components to functional groups and the boundaries across which energy flows must be measured or balanced.	`s223:hasRole` with values from `s223:EnumerationKind-Role` (zero or more per component), extended by TBSys for roles beyond ASHRAE 223; grouping and balance boundaries via TBSys constructs.
Technical properties	Static component properties evaluated by capacity- or performance-dependent placement rules, such as nominal thermal power or nominal volume flow rate.	`tbsys:hasTechnicalAttribute` → `s223:QuantifiableProperty`, including the property value, `qudt:hasQuantityKind`, and `qudt:hasUnit`.

2.2 Rule-based derivation of the metering concept

The metering concept is derived by combining two external references with a graph-based method developed in this work.

EN 17267 (DIN, 2020) introduces the levels Base, Medium, and High for the qualitative assessment of a measurement system. In the standard, these levels cover not only the available measurement points, but also data acquisition, transmission, storage, analysis, and visualisation. They therefore do not constitute meter-placement levels for an energy flow diagram. In this work, the three level names and their progression in measurement depth are adapted to define three cumulative levels of the metering scope.

The component-specific measurement requirements are taken from AMEV Technical Monitoring 2025, Recommendation No. 178, Annex 5 (AMEV, 2025). The catalogue specifies the quantities to be considered for different equipment types, identifies mandatory and optional quantities, and defines applicability thresholds for selected equipment. This work maps the relevant AMEV quantities to the three metering scopes and translates them into graph-based placement rules. The cumulative scope definition, the topological placement patterns, their implementation as graph queries, and the handling of overlapping rules are therefore contributions of the proposed method.

Tab. 2: Sources and methodological contribution of this work.

Basis	Relevant content	Role in the method
EN 17267 (DIN, 2020)	Base, Medium, and High levels; principles concerning measurement boundaries, energy uses, and energy-flow mapping.	Conceptual and terminological basis for structuring the metering scope.
AMEV Technical Monitoring 2025, Annex 5 (AMEV, 2025)	Component-specific measurement quantities, mandatory/optional classification, and applicability thresholds.	Basis for determining which physical quantities must or may be measured for each equipment type.
This work	Cumulative metering scopes, topological placement patterns, graph queries, conflict resolution, and provenance tracking.	Automated derivation and machine-readable representation of the metering concept.

The three metering scopes are defined in Table 3. Each is cumulative — Medium includes all Base measurements and High includes both — so that selecting a scope returns every measurement up to and including it.

Tab. 3: Cumulative metering scopes defined in this work.

Level	Definition in the method	Included measurements
Base	Minimum metering required to capture the main energy inputs, outputs, conversion processes, and consumer supplies represented in the energy-flow model.	Energy flows crossing the selected system boundary and the applicable mandatory energy measurements from the AMEV catalogue.
Medium	Extends Base with additional measurements for component and subsystem balances and for a more detailed separation of distribution, transfer, storage, and end-use flows.	Selected optional AMEV energy measurements and additional meters required for distribution, transfer, storage, and component-level energy balances.
High	Extends Medium with detailed component-level measurements of operating and auxiliary media for in-depth technical monitoring.	Selected optional AMEV measurements such as condensate, humidifier water, or make-up water, provided that the corresponding media flow is explicitly represented in the graph.

These scopes concern meter selection and placement only; they do not extend to the broader measurement-system assessment of EN 17267 (Annex B).

Within each scope, the metering requirements are expressed as placement rules, each associated with a recurring structure in the energy-flow model. Table 4 lists the rules, the resulting meter placement, and their basis — whether the underlying measurement requirement originates from AMEV, the general concept from EN 17267, or the graph-placement logic from this work.

Tab. 4: Meter-placement rules by metering level and methodological basis.

Level	Rule category	Meter placement	Basis
Base	System boundary	Place one meter on each relevant incoming or outgoing energy flow that crosses the selected system boundary.	Boundary and energy-flow principles from EN 17267; graph rule developed in this work.
Base	Generation and conversion	For equipment mapped to an applicable AMEV generator or converter category, place meters on the required energy inputs and useful-energy outputs after evaluating the corresponding threshold conditions.	AMEV Annex 5; equipment mapping and topological placement developed in this work.
Base	End-use supply	Place a meter on the incoming energy flow of a relevant consumer group where separate consumption measurement is required by the selected scope.	AMEV Annex 5; graph-based resolution of the consumer connection developed in this work.
Medium	Distribution branches	Place meters on the relevant outgoing branches of a distribution node. Add a meter on the common inlet only where a complete distribution balance is required and the inlet is not already metered.	AMEV measurements for heating and cooling circuits; general branch rule developed in this work.
Medium	Air-handling unit coils	Place a thermal-energy meter on the connection supplying a heating, cooling, or reheat coil when the corresponding optional measurement is included in the selected scope.	AMEV Annex 5.
Medium	Energy transfer	Place a meter on the energy flow transferred across a heat exchanger or system interface. Meter both sides only where a complete transfer balance is required.	AMEV examples for transfer equipment; general interface rule developed in this work.
Medium	Storage charging and discharging	Place meters on the charging and discharging connections where a storage energy balance is required. The hydraulic topology determines whether separate or bidirectional measurements are necessary.	Topological extension developed in this work; separate charge/discharge meters are not generally specified for buffer storage in AMEV Annex 5.
Medium	Auxiliary electrical loads	Place an electricity meter on the supply connection of an auxiliary unit, such as a fan, pump, or recooling unit, where its consumption is to be recorded separately.	Component-specific requirements and examples from AMEV Annex 5.
High	Operating media	Place a meter on an explicitly modelled component-level media flow, such as condensate, humidifier water, or make-up water, where the corresponding optional AMEV quantity is included in the selected scope.	Optional quantities from AMEV Annex 5; graph applicability condition developed in this work.

For a selected metering-scope level, the Graph Engine derives the concept in four stages. First, it identifies the equipment instances and recurring topological structures in the graph. Second, each equipment instance is mapped to the applicable AMEV equipment category, and any associated capacity threshold is evaluated. Equipment instances are mapped through an explicit class-mapping table, with label-based matching used only where no direct ontology mapping is available. Third, the applicable AMEV measurement requirements and the additional topological requirements defined in this work are translated into placements on specific graph connections. Finally, duplicate placements are consolidated, and the resulting meter entities — together with their level, triggering rule, and source reference — are written back into the knowledge graph.

Each placement rule is implemented as a graph-pattern query over the system topology. The query identifies the relevant equipment and graph connection and determines the required meter type. The meter type is derived from the energy classification assigned to the connection, which may represent a general energy carrier or, for thermal flows, distinguish between heating and cooling energy. The query result is then used to create the meter entity on the identified graph connection.

Applicability thresholds specified by AMEV are evaluated before a component-specific requirement is activated. If the required technical property is unavailable, the requirement is marked as not assessable. If several rules identify the same connection, duplicate placements are consolidated while retaining their rule provenance. If a required energy supply is missing from the input graph, the requirement is recorded as unresolved; any inferred connection is explicitly marked as such and requires review.

2.3 Data binding and Sankey energy flow diagram generation

The metering concept generated in the previous step is initially structural: it defines the meter type and placement but does not yet contain measured values. Each meter is linked to its corresponding time series using the Brick time-series reference model (Balaji et al., 2016). The observable property associated with the meter contains a ref:hasTimeseriesReference, which identifies both the channel (ref:hasTimeseriesId) and the external data store (ref:storedAt). The association between a meter and its measured data is thus stored directly in the knowledge graph rather than maintained in a separate mapping table. For a selected evaluation period $[t_0, t_1]$, the referenced time series is aggregated to obtain the energy value represented by each metered connection.

The Sankey diagram is generated from the system topology and the functional roles assigned to the components. These roles describe the position of each component within the energy supply chain, including source, generator or converter, storage, distributor, and consumer. Heat exchangers are treated as transfer elements between the corresponding system sections. Equipment instances form the principal Sankey nodes, while connective elements such as meters and connection points are omitted from the visualisation. The aggregated meter values are assigned to the corresponding energy-flow connections.

The resulting flows are additionally classified using selected energy-flow categories and notation from DIN V 18599 (DIN, 2018). Since the same energy carrier may occur at different stages of the energy supply chain, the flow category is determined from the functional roles of the upstream and downstream components rather than from the energy carrier alone. The corresponding DIN V 18599 category is then assigned based on this role transition.

3. Results and discussion

3.1 Demonstrator building and reference metering concept

The case-study building is a net-zero-energy demonstration facility comprising office space and an experimental hall (Tomás et al., 2025). Heating and cooling are supplied using groundwater from a single well. For heating, the groundwater serves as the heat source for a 75 kW water/brine heat pump. The generated heat is buffered in a storage tank before being distributed to the consumers. For cooling, the groundwater supplies three plate heat exchangers that provide direct free cooling without operation of the heat pump. A central distribution system serves five consumer groups with distinct thermal requirements: thermally activated building systems in the office wing, a laboratory, server rooms process cooling, and an air-handling unit for general ventilation. The corresponding plant schematic is shown in Figure 2.

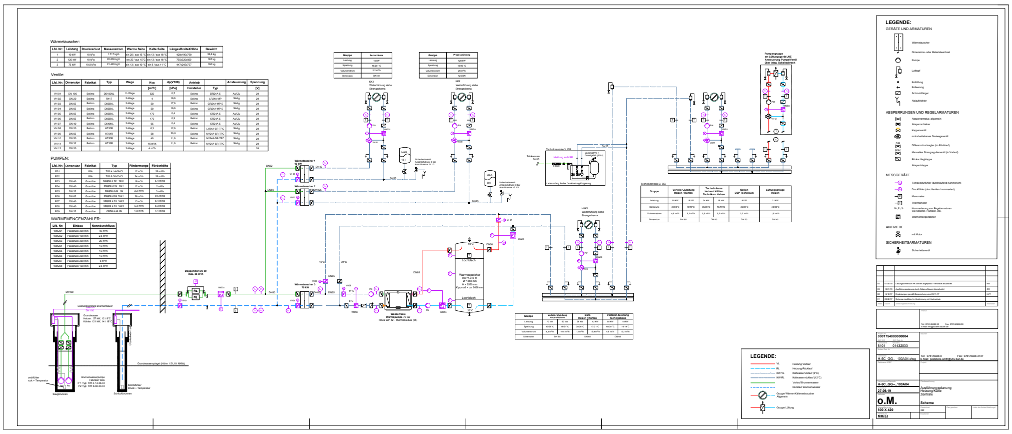


Fig. 2: Plant schematic of the case-study building's heating and cooling system, used as the basis for creating the graph and reference metering concept.

Figure 3 shows the reference metering concept as a single-line energy-flow diagram of the heating and cooling system. It was derived manually from the plant schematic and the available hydraulic documentation. Meter types are assigned according to the energy carrier and thermal function of each flow: heat meters are used for the heat-pump and heat-storage branches, cooling meters for the direct groundwater cooling branches, and bidirectional heat/cooling meters where the same distribution path alternately supplies heating and cooling, as in the laboratory and office branches. The reference concept comprises ten meters, including eight thermal and two electrical meters, and is used for the evaluation in Section 3.3.

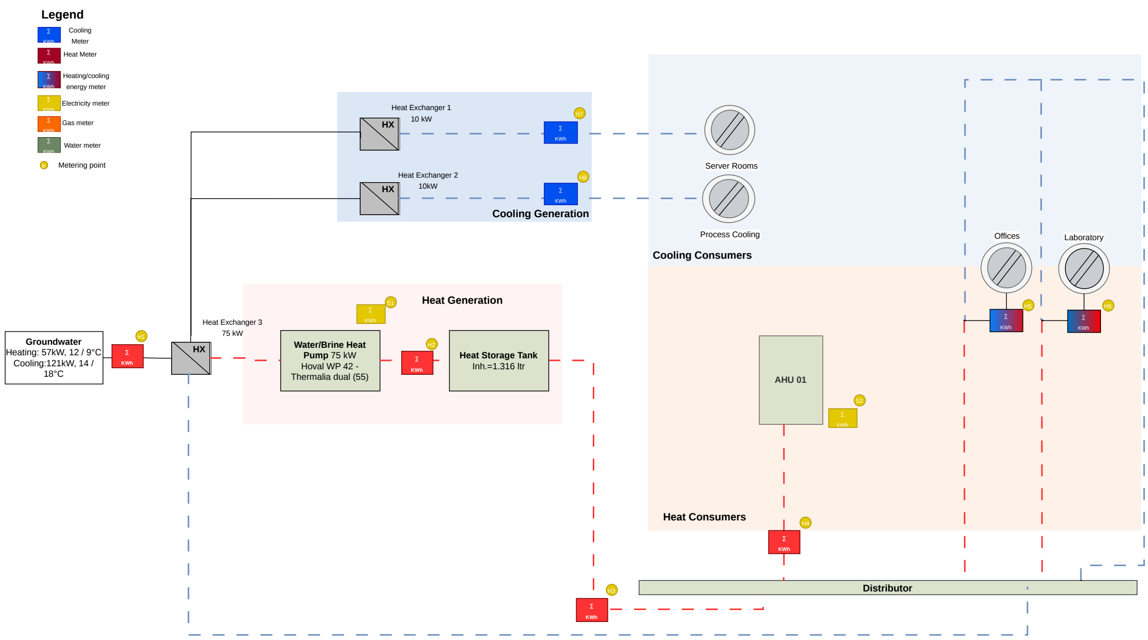


Fig. 3: Reference metering concept for the heating and cooling system of the case-study building, represented as a single-line energy-flow diagram.

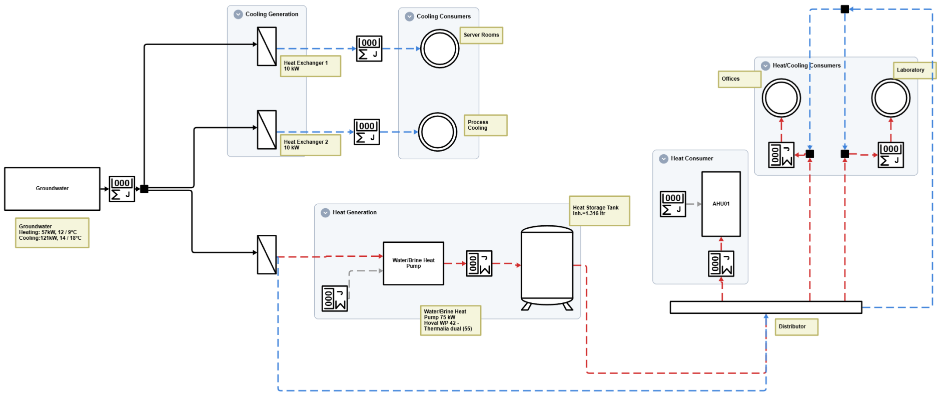
The proposed method generated cumulative metering concepts for the demonstrator building at the Base, Medium, and High scopes. Figure 4 compares the Base and Medium concepts. The High-scope result is identical to the Medium-scope result because the graph contains none of the operating-media flows addressed exclusively by the High-scope rules.

The Base scope comprises nine meter placements and covers the main energy path from source to end use. A meter is placed on the groundwater flow leaving the source, thereby quantifying the environmental energy supplied to the system. Further placements capture the energy conversion at the heat pump and the energy supplied to the relevant consumer groups. The Base concept therefore provides measurements for the principal source, conversion, and end-use flows represented in the model.

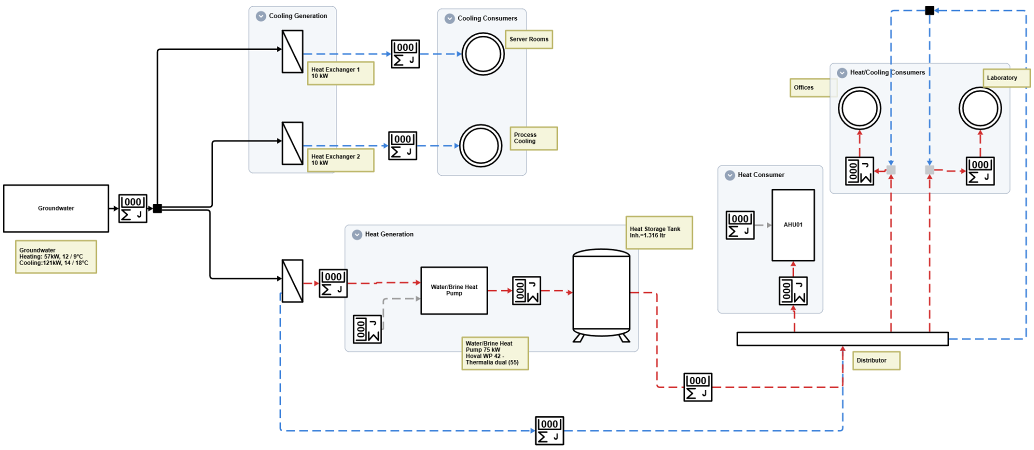
The Medium scope retains all Base-scope placements and adds three meters for a more detailed assessment of transfer and storage processes. Two additional meters are placed at the groundwater heat-exchanger connections. A further meter is placed on the storage discharge connection; together with the meter already located on the charging path, this enables the thermal storage to be balanced. The Medium concept thereby supports a more detailed separation of the source, heat-transfer, storage, and consumption stages.

The graph does not explicitly represent every electrical supply connection required by the applicable rules. Where such a connection is missing, an inferred connection is added and marked for engineering review. In the demonstrator building, this applies to the electrical supplies of the heat pump and the air-handling unit. The inferred connections are shown as grey dashed lines in Figure 4.

The Medium/High concept matches all ten meter placements in the reference concept and contains two additional placements at the groundwater heat-exchanger connections. Both additional placements result from the Medium-scope energy-transfer rule.



(a) Base scope.



(b) Medium scope (identical to High).

Fig. 4: Generated metering concepts for the demonstrator building at the Base and Medium scopes, visualised in the DiMASH-App.

Tab. 5: Generated meter placements for the demonstrator building at the Base, Medium, and High scopes.

Metering scope	Number of meters	Placements by rule category
Base	9	1 system-boundary, 1 generation and conversion, and 7 end-use supply placements.
Medium	12	Base placements plus 2 energy transfer (heat-exchanger-connection) and 1 storage charging and discharging placement.
High	12	Identical to Medium; no High-specific operating-media flows are represented in the model.

3.2 Sankey diagram results

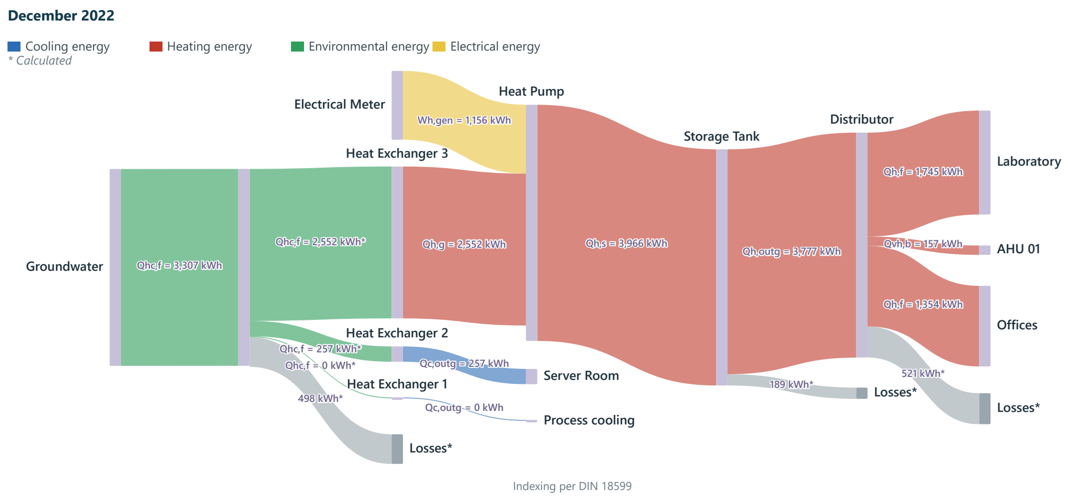


Fig. 5: Sankey diagram of the demonstrator building for December 2022 (heating operation), showing measured and calculated energy flows.

The Sankey diagram in Figure 5 was generated from the graph and the linked meter time-series. The Sankey structure, including the equipment nodes, their ordering, the energy-flow connections, and the corresponding DIN V 18599 indices, is derived automatically from the graph, while the flow values are obtained from the linked meter time-series; no building-specific mapping is required for diagram generation. Measured energy values are assigned to the corresponding energy-flow connections, while calculated values are marked with an asterisk.

The grey flows labelled "Losses*" are calculated from the balance between incoming and outgoing energy flows and are not independently measured. They may therefore include actual thermal losses as well as effects of measurement uncertainty, unrepresented flows, or changes in stored energy.

The heat-pump measurements do not form a closed energy balance. The thermal source input of 2,552 kWh and the electrical input of 1,156 kWh result in a combined measured input of 3,708 kWh, compared with a measured thermal output of 3,966 kWh. The difference of 258 kWh corresponds to approximately 6.5 % of the measured thermal output. Since this discrepancy cannot be interpreted as a physical loss, it is retained rather than forcing the balance to close. Possible causes include measurement uncertainty and incomplete or non-synchronous time-series data.

3.3 Comparison with expert-prepared reference concepts

To evaluate the transferability of the proposed method, it was applied to two additional building energy systems with different configurations and levels of technical complexity. Building 2 comprises approximately

66 components and includes a district-heating connection, several air-handling units, compression chillers, recooling equipment, and buffer storage. Building 3 comprises approximately 72 components and combines solar thermal collectors, heat pumps, a gas boiler, chillers, and several air-handling units. For both buildings, independently prepared reference metering concepts were available, based on the available plant schematics and system documentation. They had been prepared before the proposed method was applied, and the placement rules were not modified based on the reference concepts.

The comparison was conducted at the Medium scope, which most closely corresponds to the level of measurement detail represented in the reference concepts, and included only meters. Since the generated and reference concepts use different meter identifiers, matching was based on the metered graph connection. For each meter, the nearest upstream and downstream equipment and the corresponding medium family were identified. A generated meter was considered a match when both concepts referred to the same equipment-to-equipment connection and medium family. Meter class was evaluated separately. For inferred connections with only one available equipment endpoint, matching used that endpoint together with the medium family. Precision describes the proportion of generated placements found in the reference concept, whereas recall describes the proportion of reference placements reproduced by the method. These metrics therefore quantify agreement with the reference concepts rather than absolute technical correctness.

Tab. 6: Comparison of generated and reference metering concepts at the Medium scope.

System	Reference meters	Generated meters	Precision	Recall
Building 2	61	53	0.79	0.69
Building 3	59	50	0.78	0.66

Across the two buildings, recall ranged from 0.66 to 0.69 and precision from 0.78 to 0.79. Generated placements not present in the reference concepts mainly occurred at heat-exchanger connections and electrical supplies whose connections were not explicitly represented in the original graphs.

Most unmatched reference placements occurred in distribution structures. The generated concepts generally placed meters on individual consumer branches, whereas the reference concepts often used shared upstream distribution connections. These placements were counted as non-matches because they refer to different graph connections, even where they address the same subsystem. A separate consistency check confirmed that generated meters were assigned to valid connections and that their meter classes were compatible with the corresponding media.

4. Conclusion and future work

This work demonstrates how an energy-flow graph can be used both to derive a metering concept and to generate a quantitative Sankey diagram from linked measurement data. The method combines the Base, Medium, and High structure adapted from EN 17267 with component-specific AMEV requirements and graph-based placement rules to determine meter locations from the system topology. Because the generated meters and their time-series references are stored in the graph, the metering concept, system topology, and measurement data remain linked. The Sankey structure can therefore be generated and populated from the same information without a separate building-specific mapping. The same placement rules were applied without modification to two additional building energy systems, indicating that the implementation is not specific to the demonstrator topology.

The present study is limited by the information available in the input graph. The energy-flow graph is currently created manually from system documentation, and missing or incorrect topology can therefore affect the derived metering concept. The rule set is also limited to meters; the Base, Medium, and High scopes defined here concern meter selection and placement and do not reproduce the full assessment levels of EN 17267. In addition, the evaluation is based on a limited number of expert-prepared reference concepts. Since different technically justified meter placements can exist for the same system, precision and recall quantify agreement with these references rather than absolute technical correctness. The quantitative Sankey results likewise depend on the quality and temporal alignment of the linked measurement data.

Future work will focus on automating the creation of the energy-flow graph from system documentation and extending the placement rules to additional monitoring quantities, including temperature, volume flow, and pressure. Evaluation on a larger and more diverse set of building energy systems is also required to assess the applicability of the rules across different system configurations. Such an evaluation should account for alternative technically justified metering strategies rather than treating a single reference concept as the only correct placement solution.

Data availability: The measurement and building-model data used in this study are internal and not publicly available.
AI-usage disclosure: AI-based tools were used to support schematic digitisation and knowledge-graph editing (Section 2.1) and for language editing; all methodological and analytical decisions were made by the authors.

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