

GIS-AWBEM: GIS-based Automated White-Box Building Energy Modeling

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Abstract—Studying urban district energy transitions requires a flexible and detailed building-specific energy performance analysis. This article presents an open-source Geographic Information System (GIS)-based framework for conducting white-box Urban Building Energy Modeling (UBEM) analysis via a bottom-up approach. The proposed methodology uses available geospatial data to construct 3D building envelopes and equip them with detailed physics-based Heating, Ventilation, and Air Conditioning (HVAC) systems. For each building, both the building envelope and energy system are modeled using the open-source building simulation software *EnergyPlus*, which is freely available and computationally efficient. The framework is applied to a typical district with 241 buildings in south-west Germany, where its capabilities are showcased by providing dynamic insights into load and HVAC system performance. Three scenarios are studied to: 1) calculate the buildings and entire district demands, 2) simulate the traditional HVAC system comprised of gas-fired boilers and cooling coils, and 3) represent the future HVAC system implementing heat pumps for both heating and cooling purposes. It is concluded that scenario 3, compared to scenario 2, increases the grid dependency by 80.5% and reduces the environmental impacts by 13.9%. Moreover, the reported low computational costs across all scenarios certify the framework applicability for further urban planning and district-scale energy system design.

Index Terms—Building Energy Modeling, District Energy Modeling, HVAC, Automated Framework, EnergyPlus

I. INTRODUCTION

The International Energy Agency (IEA) reports that the building sector accounts for 30% of global energy consumption and 26% of global CO₂ emissions [1]. To reduce the environmental impact, the building sector must become more efficient [2]. Building design, energy-consumption monitoring, and retrofitting can contribute to energy-consumption reduction in buildings [3]. Urban Building Energy Modeling (UBEM) tools integrate and analyze these aspects to optimize building operations and facilitate the planning of efficient district energy systems [4]. According to Deng et al. [5], two main directions in UBEM exist: an aggregation approach, which provides fast building load estimation, and a building-by-building approach, which accounts for interactions among individual buildings and captures refined energy profiles. For a comprehensive and detailed analysis of urban areas, two types of information are needed: (i) passive building properties, e.g.,

building shape, height, orientation, zoning, isolation...; (ii) active properties, ones that can be directly assessed, such as Heating, Ventilation, and Air Conditioning (HVAC) operations and internal gains (e.g., occupants, lights and electrical appliances). However, modeling urban areas (e.g., cities or districts) is challenging because data are often scarce and the modeling effort is high [6], as model parameterization is usually time-consuming. Thus, according to Jansen et al. [2], significant efforts are made to automate modeling and parameterization to reduce time and costs. Existing approaches in literature have addressed this issue; however, several drawbacks remain, including partial process automation, limited availability of open data, and reliance on idealized Building Information Modeling (BIM) data.

A. Related work

Schiefelbein et al. [6] proposed a methodology for generating urban building models using open-source Geographic Information System (GIS) tools combined with Open Street Map (OSM) [23] data. Reduced-Order Model (ROM), also known as Resistor-Capacitor (RC) model, is used to parametrize the building envelope, and to enhance model accuracy, the dataset is refined by incorporating national building-stock statistics. The approach was evaluated through a case study involving 55 residential buildings, in which space heating net energy demand was simulated, and the resulting models were validated against measured energy consumption. Battini et al. [7] introduced a methodology for modeling buildings with complex geometries by simplifying them into “shoebox” representations, which was motivated by the need to accelerate urban-scale building energy simulations, and the influence of surrounding structures was incorporated. Similarly, Prativiera et al. [8] presented a platform for bottom-up, open-source thermal building modeling based on the ROM, which was computationally efficient. Their work included analyses of various RC configurations and their accuracy, as well as forecasts of district-level energy demand. On the other hand, Heidenthaler et al. [9] developed an automated urban building energy modeling framework that employs a detailed, bottom-up physical modeling approach to predict hourly residential space-heating and domestic hot-water loads. The results were

evaluated using two district heating network measurements and TABULA typology [10]. Once the suitable district cluster and boundaries are defined [11], the related Building Energy Modeling (BEM) framework can be employed. Buonomano et al. [12] proposed a Geographic Information System (GIS)-based framework to model and aggregate energy demand in energy communities and to assess planning strategies to optimize their self-sufficiency and life cycle costs. Ali et al. [13] proposed a universal bottom-up approach for urban building energy modeling based on GIS data. A case study in Dublin applied the methodology and used energy performance certificate data to emphasize the role of the bottom-up energy analysis approach in improving policy and urban planning decisions. Jansen et al. [2] proposed an open-source framework, *bim2sim*, containing a modular structure and an interface to multiple simulation tools, such as Modelica [14] and EnergyPlus [15]. The framework uses BIM data and Industry Foundation Class (IFC) files to build white-box models for building energy performance analysis. One common issue in such framework operations is the availability and quality of framework input data, which are significant for reducing uncertainty in results. Geiger et al. [16] developed an approach to assess the completeness, correctness, and consistency of open Building Information Modeling (openBIM) data, thereby determining the suitability of the data before running computationally intensive simulations. Moreover, Schildt et al. [17] and Geiger et al. [18] emphasized and provided solutions to enrich the accuracy and classify the building physical properties to conduct UBEM analysis, including building archetype, Level Of Detail (LOD), thermal properties of building material, and Window-to-Wall Ratio (WWR).

B. Contributions

As elaborated in the previous section, most existing works reduce the complexities of the building envelope using ROM or use an idealized energy system to estimate building demand only, or rely on publicly unavailable building data to obtain detailed building parameters (e.g., IFC files).

To fill the identified research gaps, this work presents an automated framework that:

- 1) employs a dynamic white-box modeling approach that entails detailed building physics, including building mass properties,
- 2) provides a detailed HVAC system enabling the design and performance evaluation of specific energy systems,
- 3) uses only one building energy simulator EnergyPlus [15], thereby circumventing the need for multiple software integrations and interface developments,
- 4) offers a modular structure, requiring only minor reconfiguration for subsequent framework implementations
- 5) is developed fully open-source to eliminate the need for commercial software.

C. Article Structure

The framework operational methodology is formulated in Section II, which describes its operative layers and compo-

TABLE I
INTERNAL GAINS AND TEMPERATURE SETPOINT REFERENCES FOR
VARIOUS BUILDING APPLICATION TYPES.

Parameter	Residential	Office / School / Commercial
Occupancy	DIN EN 16798-1 [19]	DIN EN ISO 13790 + DIN EN 16798-1
Lights	DIN EN 16798-1	DIN EN 16798-1
Electric equipment	DIN EN 16798-1	DIN EN 16798-1
Ventilation	DIN 1946-6 [20]	DIN EN 16798-3 [20]
Temperature setpoint	DIN EN 16798-1 + DIN EN ISO 13790 [21]	DIN EN 16798-1 + DIN EN ISO 13790

nents. In Section III, a test case in south-west Germany is selected to apply the framework and illustrate its functionalities in an urban district. Section IV concludes the key findings, contributions, existing limitations, and potential future works.

II. METHODOLOGY

The GIS-based Automated White-Box Building Energy Modeling (GIS-AWBEM) framework automates dynamic building energy analysis using a white-box modeling technique. It employs a bottom-up modeling approach and is tailored for urban districts and neighborhoods. As illustrated in Fig. 1, it consists of four different layers: 1) Input, 2) Data Processing, 3) Modeling and Scaling, and 4) Output Reports. This framework is developed modularly, with each layer composed of independent modules, enabling the user to reconstruct the framework with only minor reconfigurations. Python is used to develop the framework, and EnergyPlus is the single energy simulation tool. The main reasons for selecting these tools are their free availability (open-source), high computational speed, and ease of use. The framework layers are elaborated in the following subsections.

A. Input Layer

Multiple input are required prior to constructing the building energy model. The available district buildings geospatial data are adapted from GIS-based sources, namely OSM in this work. OSM contains fundamental data representing the building geometry, such as building footprints and floor surface area. Additionally, yet essential, data are required to conduct UBEM analysis, including building height, archetype, and construction year. This missing information is obtained from additional sources (e.g., census data, municipality reports, and related). Meteorological conditions are essential for describing the thermal interaction between buildings and their surroundings. This input can be obtained from the nearest weather station as weather data. Depending on the building application type, heating and cooling setpoint temperatures are set based on occupant preferences, organizational policies, building codes, or a combination of multiple standards and norms. The last necessary input is the set of building internal heat gains, including heat generated by occupant metabolism, lighting, and electrical equipment, and thermal losses due

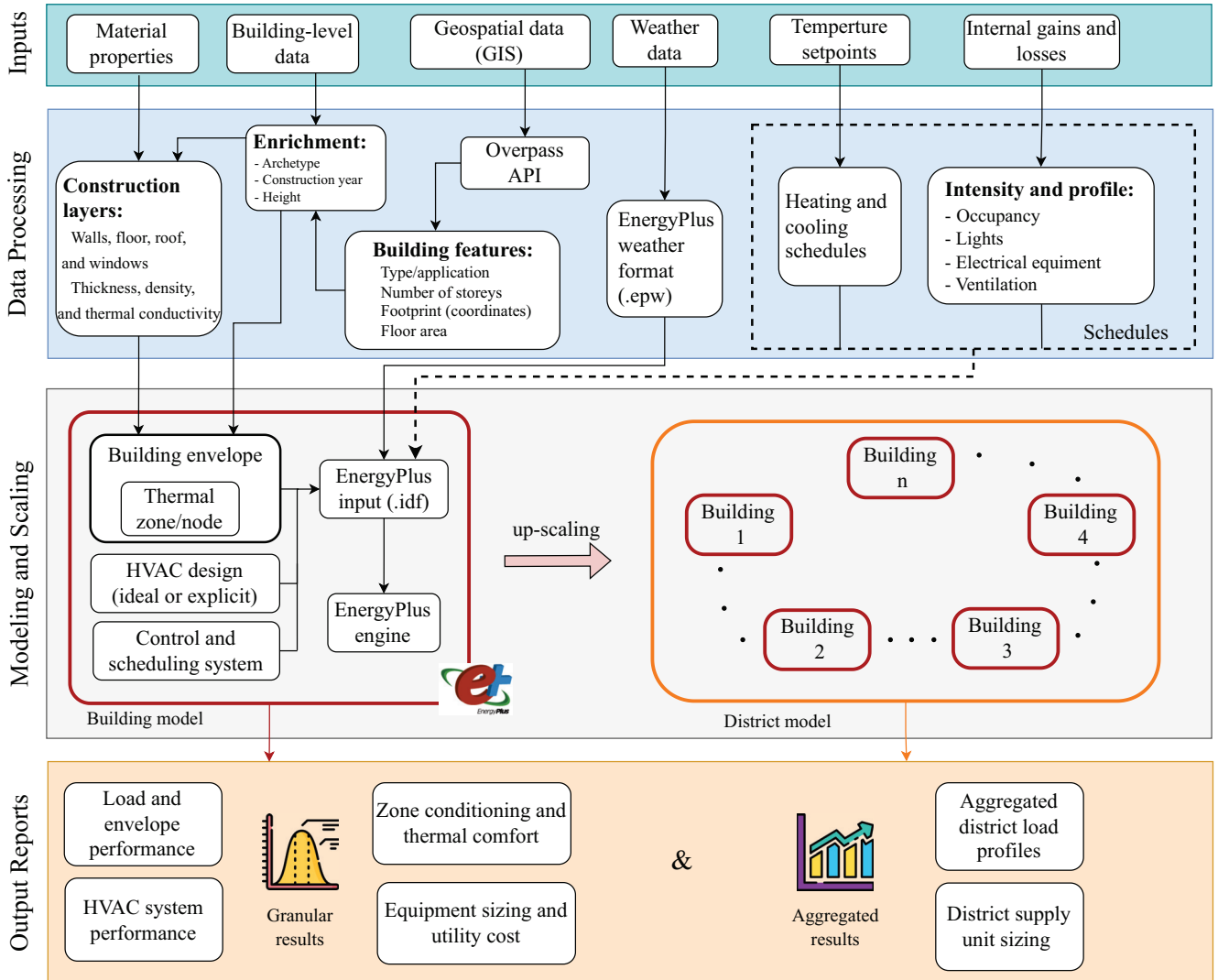


Fig. 1. GIS-AWBEM framework illustrating the operative layers and modules.

to the exchange of indoor air with fresh outdoor air. A compilation of these parameters is given in Table I.

B. Data Processing Layer

The raw or queried data from the input layer is imported into this (data processing) layer. The goal is to reshape, enrich, and prepare the input for the simulator engine, i.e., EnergyPlus. The Overpass API (<https://overpass-turbo.eu>) queries geospatial data for a specific area, limiting the district boundaries. After the data export, the buildings' footprints, usage applications, number of levels, etc., are available in GeoJSON or KML formats. In case of data availability, further enrichment to improve the building envelope characteristics is envisioned to equip the building with more accurate archetype, construction year, and height. The building archetype and construction year are crucial for identifying the specific material type used, which subsequently affects the construction layers of the external building surfaces. The weather data is processed

for quality checks and converted to the standard EnergyPlus Weather (EPW) format. Temperature setpoints and internal gains and losses are reshaped in EnergyPlus schedule formats. Both schedules and weather data are directly sent to the final EnergyPlus Input Data File (IDF).

C. Modeling and Scaling Layer

In this layer, individual building energy models are built and subsequently up-scaled to all district buildings. First, the building envelope is constructed as LOD1.2 [22] and uses both enriched geospatial data and construction and material properties. The building conditioned volume is defined by a single thermal zone (hereinafter referred to as the zone). Furthermore, the zone properties are introduced, including both geometry (floor area and volume) and algorithm selection to solve the zone inside and outside surface convective heat transfers. Second, the HVAC system is designed and added to the building model. The user can select among ideal HVAC

systems or develop a realistic and detailed energy system in which the system units are explicitly defined. The ideal HVAC is intended to calculate building demands only, while the detailed HVAC is capable of modeling equipment physics, introducing unit capacity and operation constraints, unit efficiency, etc. A wide range of HVAC units is available in the built-in EnergyPlus library for designing heating and cooling supply systems, including Direct Expansion (DX) coils, fans, boilers, radiators, heat pumps, etc. Third, control mechanisms (e.g., setpoint manager and operational schemes) are introduced to explicitly control the operation of each HVAC unit. These three steps are translated into the EnergyPlus IDF using the EnergyPlus Python library (EPPY [24]) and then solved by the EnergyPlus simulation engine. The same process continues for other district buildings, and the user can configure each previous step differently for each building and populate the entire district.

D. Output Reports Layer

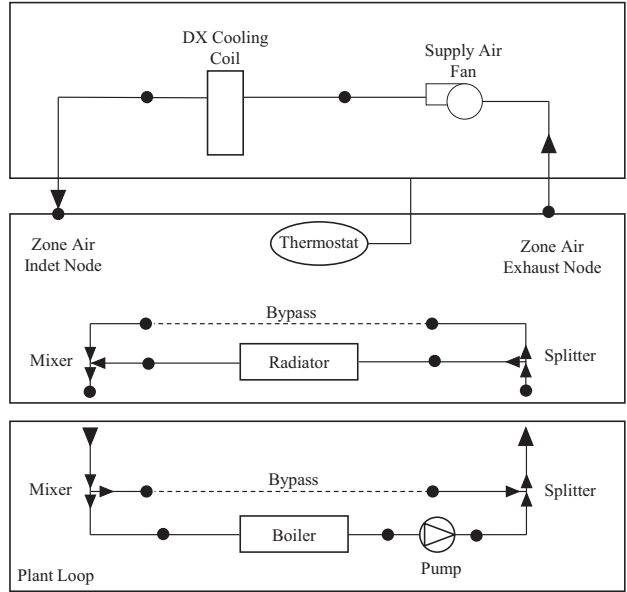
EnergyPlus provides numerous variables and meter reports after the simulation concludes [15]. The dynamic performance of the building envelope, occupant thermal comfort, load calculations, performance, and the sizing of HVAC system units are the most significant technical outputs. Implementing the bottom-up modeling approach, district performance is derived by aggregating building-level performance results.

III. CASE STUDY AND SCENARIOS

The case study is a district named Bergwald, located in the city of Karlsruhe, Germany. It is approximately 220-260 m above sea level [25] and its geographical coordinates correspond to 48.9723° N and 8.4648° E. The district comprises 241 buildings, mostly with residential applications [26]. Geospatial data for all district buildings is queried from OSM [23] via the Overpass API to obtain building footprints and floor counts. The building archetype and construction year are sourced from [28], and the building height from [27]. To introduce both the thermal conductivity and storage capacity of building materials, construction layer thicknesses and material properties are taken from [17]. WWR and the window thermal conductivity are adapted from [17] and [29] respectively. The weather data is provided by the German Weather Service (DWD) measured at the closest district weather station located in Rheinstetten [30]. Internal gains and temperature setpoints are imported as previously explained in Table I.

Three scenarios are studied in this test case to highlight the capabilities of the framework. All scenarios employ a common methodology for constructing the building envelope and differ in their energy supply system. Scenario 1 employs an ideal HVAC air load system to ideally estimate zone thermal demands without designing a specific HVAC system. Scenario 2 employs gas-fired boilers and DX cooling coils to provide heating and cooling, respectively, representing the traditional energy systems in most German residential areas. As shown in Fig. 2, the plant loop is comprised of a heat source (i.e., boiler) and a circulation pump and is responsible for supplying

Scenario 2



Scenario 3

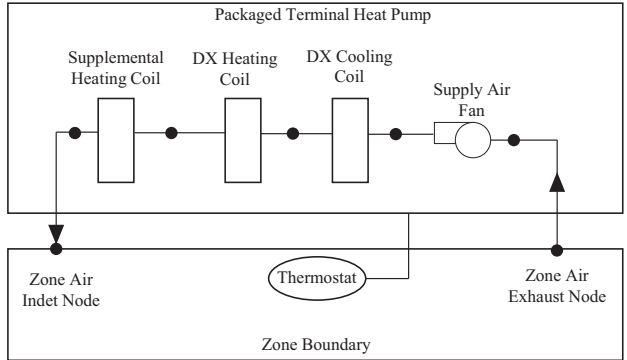


Fig. 2. HVAC system scheme of scenario 2 (top) and scenario 3 (bottom) based on [15]. Scenario 1 is not depicted since it does not contain a HVAC system.

heating energy to the zone heat sink (i.e., radiator). The air-conditioners consist of a DX cooling coil and a supply air fan to transfer the cooling energy via an air loop to the building zone. In contrast, scenario 3 replaces the boilers with air-source heat pumps and represents a modern HVAC system for both heating and cooling. A common type of air-source heat pump, Packaged Terminal Heat Pump (PTHP), is dedicated to supplying the zone with warm or cold air stream. The system primarily includes a supply air fan, DX heating and cooling coils. A supplemental heating coil is installed if the main heating coil fails to perform adequately, as illustrated in Fig. 2.

A. Results and Discussions

All scenarios are evaluated with an hourly time step over an annual time horizon based on 2024 weather data. The HVAC units are internally dimensioned in EnergyPlus based

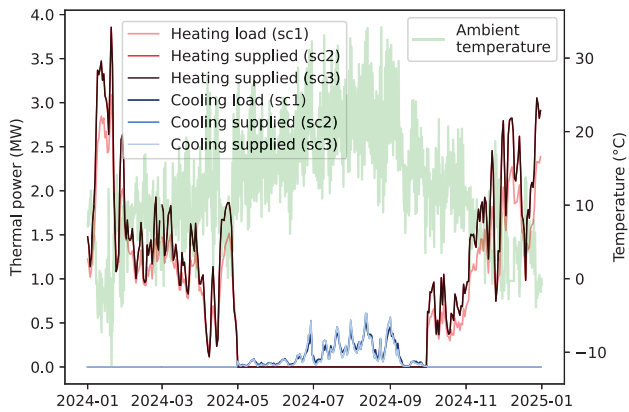


Fig. 3. Daily averaged heating and cooling loads and supplied energy of all scenarios, based on 2024 weather data for the entire Bergwald district.

on extreme weather conditions to ensure that they meet peak heating and cooling demands. Fig. 3 illustrates the aggregated daily averaged heating and cooling energy of the entire district in all scenarios. Scenario 1 calculates the thermal demand and reports aggregated annual heating and cooling loads of 6337 MWh and 526 MWh for the whole district. Results for both scenarios 2 and 3 show higher thermal energy generations than in scenario 1, which stems from the non-ideal efficiencies and operating limitations of the employed HVAC units. Scenarios 2 and 3 exhibit almost similar thermal energy generation, but they differ in their primary energy consumption. In scenario 2, the gas-fired boilers consume 964 222 m³ of natural gas and 219 MWh of HVAC electricity consumption, whereas scenario 3 eliminates any trace of gas consumption and estimates an HVAC electricity load of 4094 MWh.

Fig. 4 depicts the cumulated primary energy consumption of all district buildings in scenarios 2 and 3. Evidently, buildings with small conditioned volumes (e.g., single-family houses) report on lower energy demands (approximately 1840 m³ of gas in scenario 2 and 12 MWh of electricity (including

both HVAC and other electrical appliances) in scenario 3), while buildings with larger conditioned volumes (multi-family houses and apartment blocks) report the highest demands (up to approximately 19 425 m³ of gas in scenario 2 and 306 MWh of electricity in scenario 3). Moreover, the annual performance metrics for all scenarios are provided in Table II, where scenario 3 shows notable emission reductions and increases in grid dependency of 13.9% and 80.5%, respectively, compared to scenario 2.

TABLE II
ANNUAL OVERALL PERFORMANCE METRICS OF SCENARIOS 1, 2, AND 3.

Scenario	Natural gas (m ³)	Electricity* (MWh)	CO ₂ (t)	Generation time (s)	Simulation time (s)
1	-	4691	1717	27.1	4.4
2	964222	4804	3685	38.2	6.4
3	-	8670	3173	45.9	8.5

* Total electricity consumption including HVAC and other appliances.

CO₂ emissions were calculated based on [31] to compare the environmental impact of two scenarios. Scenario 2 emits 3685 t CO₂ annually due to natural gas combustion in boilers and electricity use for cooling and other building equipment. Scenario 3 eliminates the district's gas consumption and reduces annual CO₂ emissions to 3173 t. All electricity is assumed to be supplied by the low-voltage grid, with no local generation or storage. Although scenario 3 increases HVAC electrification and grid reliance, it achieves lower emissions than scenario 2. This comparison constitutes an initial step for future urban planning and district-level infrastructure design.

Another important performance metric is the runtime duration of the framework operation. The generation of IDF files and the simulation runtime for both scenarios are performed on a 13th Gen Intel(R) Core(TM) i7-1355U processor with 32GB of installed RAM. Across the district, the EnergyPlus IDF generation times are 27.1 min, 38.2 min, and 45.9 min for scenarios 1, 2, and 3, respectively. The increased HVAC system complexity is reflected in the simulation runtime with 4.4 min, 6.4 min, and 8.5 min for the same order.



Fig. 4. Annual district gas consumption in scenario 2 (left) and electricity consumption in scenario 3 (right). Created with Google Earth Pro.

IV. CONCLUSIONS AND FUTURE WORK

This work presents an open-source GIS-based automated framework for conducting bottom-up building energy modeling at the district scale. It offers a physics-based white-box modeling approach to both building envelope and supplied HVAC system design. The building envelopes are constructed based on available open-source data containing building footprint, height, and construction year, as well as thermal properties of building construction materials such as density, thermal conductivity, and layer thickness. Three scenarios are designed to study and compare the performance of different HVAC systems. An ideal air-load system is used in scenario 1 to calculate only the building thermal demands. Scenario 2 represents the current energy system state of many buildings, using gas-fired boilers in the cold season and direct-expansion cooling coils in the warm season. In scenario 3, air-source heat pumps are implemented for both heating and cooling purposes to represent a possible future state of fully electrified HVAC systems. These scenarios are applied to a district test case with 241 buildings in south-west Germany. The proposed framework is shown to be capable of handling all three scenarios at low computational cost. The district thermal loads are estimated using scenario 1. A comparison of two other scenarios indicates that the HVAC system designed in scenario 3 yields greater grid dependency and lower CO₂ emissions than the one in scenario 2. As future work, the GIS-AWBEM can be extended to larger districts and larger city quarters to provide more detailed and dynamic energy performance data. Moreover, the framework can be combined with parallel tools to extend the dimensionality of the analysis of district energy performance, for example, by integrating automated GIS-based low-voltage distribution grid generation [32].

OPEN-SOURCE CODE AVAILABILITY

The source code of the GIS-AWBEM framework is available at <https://github.com/KIT-IAI/GIS-AWBEM>.

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