Interactive 3D Energy Visualization Model for Campus Energy Awareness

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Abstract

Engineering programs increasingly integrate sustainability, data visualization, and experiential learning to prepare students for systems-level challenges in energy and infrastructure. This paper presents a senior design case study in which a student team developed an interactive, dual-modality 3D campus energy visualization platform that combines a digital campus model with a synchronized physical 3D-printed representation. Leveraging Building Automation System (BAS) data, the project explores how campus infrastructure can serve as a place-based learning context that connects technical work to familiar environments.

Guided by the research question of how campus energy infrastructure can function as an authentic capstone platform, the paper documents system architecture, instructional design, and assessment methods, including rubric evaluation and student reflections. Findings suggest that integrating operational infrastructure data with visualization and physical computing supports interdisciplinary integration, systems thinking, and professional communication while fostering a sense of contribution to campus sustainability. This work contributes a practical example of infrastructure-centered capstone pedagogy and an assessment approach applicable across institutional contexts.

Keywords

Campus Sustainability, Capstone Design, Education Pathway Elements & Transitions, Energy Visualization, Teaming Pedagogy & Leadership Development, Technology & Modality

Introduction

Universities increasingly serve as living laboratories for sustainability education, where infrastructure and operational data provide authentic learning contexts. This aligns with engineering education trends emphasizing project-based learning, data-informed design, and stakeholder interaction for developing technical competence and professional identity [1], [2]. As energy systems grow more complex and data-driven, engineers must integrate analysis, communication, and sustainability considerations [3].

Visualization technologies and physical computing platforms enable learners to interpret infrastructure behavior through interactive and tangible representations [4], [5]. Infrastructure-centered projects further strengthen engagement by connecting technical work to spaces students regularly inhabit, reinforcing personal relevance and situated learning [7], [8].

Despite growing interest in living-laboratory approaches, limited research documents how capstone projects integrating digital visualization, physical modeling, and operational data can be assessed for learning outcomes. This study addresses that gap through a case study of a senior design team developing a dual-modality campus energy visualization system. The work pursues three objectives: demonstrating infrastructure as a place-based learning platform, documenting visualization architecture, and describing an assessment approach for student learning within such contexts.

Related Work and Educational Context

Recent work in engineering education highlights the growing role of visualization and digital-twin concepts in supporting systems thinking and data literacy among students. Interactive modeling environments and data-driven interfaces enable learners to explore dynamic infrastructure behavior, helping bridge theoretical analysis and real-world system understanding [5]. Parallel work in sustainability-focused project-based learning demonstrates that authentic, real-world contexts can enhance student motivation, deepen conceptual understanding, and reinforce professional identity development [2], [6].

Physical computing and fabrication-based learning approaches, including 3D printing and embedded systems integration, have also gained attention as mechanisms for fostering multidisciplinary problem solving and hands-on engagement. These modalities allow students to translate abstract computational models into tangible artifacts, promoting iterative design thinking and collaborative learning [7]. When combined with operational infrastructure data, such as building automation or energy management systems, these approaches create opportunities for students to engage with authentic constraints related to cybersecurity, data governance, and stakeholder communication [8].

Within sustainability education, universities are increasingly conceptualized as living laboratories, where campus infrastructure serves as both a research asset and an educational platform. Prior studies have shown that infrastructure-centered learning environments can support place-based engagement and connect students' technical work to institutional sustainability goals [6]. Such contexts align with situated learning theory, emphasizing that knowledge develops through participation in authentic practices embedded within real organizational settings [9].

Despite these advances, relatively few studies have examined how infrastructure-centered capstone projects integrate digital visualization, physical modeling, and authentic operational data within a single learning experience. Moreover, limited work has documented assessment strategies capable of capturing student learning outcomes and place-based engagement within such projects. This gap motivates the present case study, which documents both the pedagogical design and assessment approach of a dual-modality campus energy visualization project within a senior design context.

Pedagogical Framework and Theoretical Grounding

This project is informed by constructivist and experiential learning theories, which emphasize the role of active engagement and reflection in developing durable conceptual understanding. Prior studies in engineering education suggest that students are more likely to internalize complex system behavior when learning activities require them to design, test, and explain artifacts that operate within real-world constraints rather than abstract problem settings [9].

The integration of operational campus energy data positions the learning environment within a situated cognition framework, where knowledge is developed in the context of authentic professional practice. Students are not only tasked with technical implementation but are also required to negotiate data access, interpret operational metrics, and present findings to campus stakeholders. These activities mirror professional engineering workflows and reinforce the social and organizational dimensions of technical decision-making.

The dual-modality structure, combining a digital visualization interface with a physical, tangible representation, also aligns with multimodal learning research, which indicates that conceptual understanding is strengthened when learners engage with both visual and kinesthetic representations of complex phenomena. In this context, the physical model serves as a cognitive bridge between numerical data and spatial reasoning, supporting learners who may struggle to interpret abstract time-series plots or dashboard-style interfaces alone.

Institutional and Course Context

The project was implemented within a two-semester senior design capstone sequence in the electrical and computer engineering program enrolling 81 final-year undergraduate students. Capstone teams typically consist of four to six students and pursue diverse project topics spanning embedded systems, power systems, software development, and interdisciplinary design. This paper focuses on a single team of five students selected as a case study due to its integration of campus infrastructure data, visualization design, and hardware–software system development.

The capstone sequence follows a structured engineering design process consisting of problem definition, architecture development, implementation, and validation. Faculty mentors provide guidance through milestone design reviews while students retain primary responsibility for system architecture, subsystem integration, and implementation decisions. Structured design reviews were conducted three times per semester, providing formative feedback on technical progress, documentation quality, and professional communication.

A distinguishing aspect of this project was collaboration with the campus facilities team, who served as external stakeholders and technical advisors. Facilities personnel provided contextual insight into Building Automation System (BAS) data, reporting practices, and constraints related to cybersecurity and data governance. Interaction with facilities staff occurred primarily through email communication supplemented by targeted feedback during milestone reviews, introducing students to professional communication expectations and operational considerations associated with infrastructure-facing applications.

To support coordination and accountability, students adopted role-based responsibilities modeled on professional engineering practice, including project management, systems architecture, data and software development, and hardware and fabrication. Faculty mentors facilitated milestone reviews emphasizing both technical integration and clarity of communication across subsystems. This role-based structure reinforced interdependence among team members while encouraging leadership, negotiation, and collaborative problem solving.

System Architecture and Technical Design

The visualization platform consisted of two synchronized components, a digital 3D visualization environment and a physical 3D-printed campus model, both driven by historical and near-real-time electricity data retrieved from the campus BAS. Following initial stakeholder consultations and faculty guidance on data access constraints, the overall architecture and implementation strategy were developed by the student team.

Digital Visualization Platform

The digital model integrated campus geographic and architectural datasets with BAS data through a layered software architecture designed by students. The architecture included:

- a data ingestion layer for retrieving power measurements through secure application programming interfaces (APIs);
- a time-series database for storing and querying historical energy data;
- a visualization engine for mapping consumption values to three-dimensional building geometries and color scales; and
- a user interface layer for building selection, trend analysis, and temporal filtering.

These design decisions required students to balance usability, performance, and data fidelity while incorporating feedback from faculty mentors and facilities professionals. The resulting platform enabled exploration of spatial and temporal energy patterns, including peak demand periods and variations across academic, residential, and administrative buildings.

Because the visualization system interfaced with operational infrastructure, students were required to address institutional cybersecurity and data governance considerations. BAS data access was restricted to read-only endpoints, and data ingestion scripts underwent facilities review prior to deployment. These constraints introduced students to professional practices related to credential management, audit logging, and system isolation, reinforcing secure design principles in infrastructure-facing applications.

Physical 3D Model and Embedded System

To complement the digital interface, students designed and fabricated a modular physical campus representation using additive manufacturing. Individual building models were assembled to reflect campus spatial layout and integrated with an embedded microcontroller system that synchronized LED indicators with digital consumption data.

Light intensity and color encoded building-level energy usage, transforming abstract numerical data into intuitive visual cues. Students developed a calibration workflow to align digital values with physical LED output, including normalization of historical demand ranges and iterative testing under simulated load conditions. This process reinforced concepts of signal scaling, quantization, and perceptual design while highlighting challenges associated with translating continuous data into human-readable formats.

Alignment with Learning Outcomes

The system architecture served as a vehicle for achieving key learning outcomes related to technical integration, systems thinking, and professional practice. Students were required to coordinate hardware and software subsystems, negotiate real-world data constraints, and document design decisions through architecture diagrams and technical reports. The dual-modality approach also encouraged students to consider multiple representations of infrastructure behavior, strengthening spatial reasoning and communication skills when explaining system functionality to diverse audiences.

An overview of the integrated digital and physical visualization platform is shown in Figure 1, illustrating the relationship between data acquisition, software visualization, and embedded physical representation.

Figure 1. Integrated digital and physical 3D campus energy visualization system

Instructional Design and Learning Outcomes

The project was structured around explicit learning outcomes spanning technical, cognitive, and professional domains. These outcomes were aligned with program-level capstone expectations and the project’s infrastructure-centered design context.

Technical Competence: Students were expected to design and integrate embedded hardware, develop data ingestion pipelines, and implement an interactive visualization interface capable of representing campus energy consumption patterns. Achieving these outcomes required coordination across software development, data analytics, and hardware integration tasks.

Systems Thinking: By engaging with operational energy data and infrastructure constraints, students developed an understanding of interactions among electrical systems, data architectures, and user interfaces. The project required consideration of spatial variability in demand, temporal load dynamics, and institutional constraints related to cybersecurity and data governance, supporting holistic reasoning about infrastructure systems.

Professional Skills: The capstone experience emphasized teamwork, project management, and communication. Students produced system architecture diagrams, interface specifications, test plans, and a formal design report while participating in milestone design reviews. Sustained interaction with faculty mentors and facilities staff reinforced professional communication norms and encouraged translation of technical findings into language accessible to non-specialist audiences.

Collectively, these instructional elements positioned the capstone experience as an integrative learning environment in which technical development, collaborative design, and reflective practice contributed to the achievement of intended learning outcomes.

Methods

This study employed a qualitative case study design to examine how campus infrastructure can function as an authentic platform for capstone learning. The case focused on a single senior design team within a cohort of 81 students enrolled in a two-semester electrical and computer engineering capstone sequence. The selected project integrated operational campus data, visualization development, and physical prototyping, providing a suitable context for exploring interdisciplinary learning processes.

Multiple data sources were used to capture evidence of student learning and project development. First, faculty mentors and external reviewers evaluated the final system using a standardized capstone rubric assessing technical integration, documentation quality, system functionality, and professional communication. Second, students submitted written reflections at project completion describing challenges encountered, perceived learning gains, and experiences working with operational infrastructure. Third, instructor observations from structured milestone design reviews (three per semester) provided additional insight into team progress, decision-making, and communication practices.

Qualitative data from reflections and review observations were analyzed using an inductive thematic approach. Responses were examined iteratively to identify recurring patterns related to systems thinking, interdisciplinary integration, and professional communication. Rubric results were analyzed descriptively to characterize overall performance and complement qualitative findings. Because the study focused on a single-team case, analysis emphasized interpretive insights rather than statistical generalization.

All student reflections and project artifacts were anonymized prior to analysis to protect participant identity and ensure compliance with institutional guidelines for educational research.

Student Learning Outcomes

Rubric-based evaluation indicated that the team met or exceeded expected capstone outcomes across technical integration, system functionality, documentation quality, and professional communication. Reviewers highlighted effective coordination between digital visualization components and the embedded physical model, reflecting strong interdisciplinary integration and system-level reasoning.

Qualitative analysis of student reflections and instructor observations provided additional insight into learning processes. Students described coordinating hardware and software subsystems, addressing data normalization challenges, and iteratively refining visualization mappings through testing cycles. These experiences contributed to the development of systems thinking, interdisciplinary integration, and professional communication competencies aligned with intended learning outcomes.

Table 1 summarizes the relationship between emergent qualitative themes, rubric evidence, and associated learning outcomes. Themes included systems thinking development, interdisciplinary integration, professional communication, iterative design and problem solving, and sustained engagement with project tasks. Together, these findings suggest that the project supported integrative learning extending beyond technical implementation by encouraging coordination across subsystems, adaptation to real-world constraints, and reflective design practices.

Table 1. Integrated Summary of Qualitative Themes, Rubric Evidence, and Learning Outcomes

Emergent Theme	**Related Learning Outcome**	**Supporting Evidence**	**Rubric Dimension**	**Observed Strength**
Systems Thinking Development	Holistic understanding of infrastructure interactions and data flow	Reflections, design reviews	Technical Integration	Effective coordination of digital and physical visualization subsystems
Interdisciplinary Integration	Integration of software, hardware, and energy data analytics	Reflections	Technical Integration	Successful combination of power systems, software, and embedded design tasks
Professional Communication	Ability to document and present technical systems effectively	Design reviews, reflections	Professional Communication	Clear architecture documentation and effective milestone presentations
Place-Based Motivation	Engagement and sense of ownership over engineering work	Reflections	Team Collaboration	Sustained engagement and collaborative coordination across project roles
Iterative Design and Problem Solving	Application of iterative testing and refinement processes	Design reviews	System Functionality	Repeated calibration and refinement of data scaling and LED mapping workflows

Although formal assessment of outreach impact was outside the scope of this study, student reflections indicated that working with familiar infrastructure enhanced motivation and perceived relevance. Demonstrations of the visualization platform in academic and informal settings provided opportunities for students to articulate technical insights and observe audience responses, reinforcing communication skills and contextual awareness.

Broader Impacts and Campus Integration

Beyond its role as a capstone learning experience, the project demonstrated potential institutional value as a visualization artifact supporting sustainability awareness and instructional discussion. The dual-modality design enabled use in classroom demonstrations and informal academic settings, where the physical model facilitated intuitive discussion of spatial energy patterns while the digital interface supported exploration of temporal trends.

Collaboration with campus facilities professionals introduced students to operational considerations related to data governance, cybersecurity, and reporting practices. Although stakeholder interaction occurred primarily through asynchronous communication and design review feedback, this engagement contextualized technical decisions within real infrastructure constraints and reinforced professional communication expectations.

While outreach interactions were not formally assessed, demonstrations of the visualization platform provided opportunities for students to articulate technical insights and observe audience engagement with energy visualization concepts. These experiences suggest that infrastructure-centered capstone projects can generate artifacts with value beyond course completion while linking student learning to institutional sustainability narratives.

Limitations

This study should be interpreted within several limitations. First, findings are based on a single-team case study within a broader capstone cohort, limiting generalizability across student populations and institutional contexts. While the project provides a detailed example of infrastructure-centered learning, additional multi-team and multi-cohort studies are needed to confirm observed learning patterns.

Second, the assessment relied on rubric-based evaluation, student reflections, and instructor observations. Although these sources enabled triangulation of qualitative insights, the study did not include pre–post measures, comparison groups, or standardized learning assessments. Consequently, conclusions regarding learning gains remain interpretive rather than causal.

Third, stakeholder engagement occurred primarily through asynchronous communication and design review feedback, and outreach activities were not formally assessed. As a result, conclusions related to institutional impact should be considered exploratory.

Finally, the familiarity of the campus infrastructure context may have influenced student motivation in ways not fully captured through available data sources. This contextual dimension may differ from outcomes observed in more abstract or externally sponsored capstone projects.

Conclusion

This study examined how campus energy infrastructure can function as an authentic platform for capstone learning through a case study of a senior design team that developed an interactive, dual-modality visualization of campus electricity use. Findings indicate that integrating operational infrastructure data with digital visualization and physical modeling can support interdisciplinary integration, systems thinking, and professional communication while providing students with opportunities to engage in engineering work situated within familiar environments.

The place-based nature of the project contributed to student motivation and perceived relevance, positioning the capstone experience not only as a technical exercise but also as a meaningful contribution to the campus community. By engaging with buildings and systems encountered in daily academic life, students demonstrated increased ownership of project outcomes and deeper awareness of infrastructure behavior and sustainability considerations.

Beyond documenting a technical artifact, this work contributes to engineering education scholarship by presenting an infrastructure-centered capstone case accompanied by an assessment approach that integrates rubric-based evaluation, reflective evidence, and observational insights. The study highlights how living-laboratory contexts can bridge academic learning and professional practice while generating artifacts with potential institutional value.

Although exploratory in scope, the findings suggest that infrastructure-centered capstone experiences offer a promising pathway for integrating sustainability, data literacy, and experiential learning within engineering curricula. Continued exploration of such approaches may support development of pedagogical models that connect technical competence with contextual awareness and community engagement.

Future Work

Future work will extend this exploratory case study through multi-team and multi-cohort investigations to examine how infrastructure-centered capstone experiences influence learning outcomes across diverse project contexts. Incorporating pre–post measures, structured reflection prompts, and expanded rubric analytics will provide more robust evidence of learning gains and enable comparison with traditional capstone formats.

Longitudinal tracking of student experiences beyond course completion may offer insight into how infrastructure-centered projects influence professional identity development, career readiness, and engagement with sustainability-oriented engineering roles. Additional research could also explore variations in stakeholder collaboration models, including synchronous interaction with facilities professionals and integration of real-time data streams, to better understand how authentic constraints shape learning processes.

Finally, future implementations may investigate the scalability of campus visualization platforms as reusable instructional and living-laboratory resources supporting interdisciplinary coursework and sustainability outreach. Such efforts could strengthen connections between student design work and campus operational ecosystems while expanding opportunities for experiential learning.

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