Lessons learned from the development and implementation of a workforce training curriculum for advanced controls for high performance HVAC systems

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ABSTRACT

Over the past decade, academic research on advanced controls has slowly transitioned into new software platforms, giving rise to various companies developing and deploying these innovative products, including solutions for light commercial HVAC systems. However, the current workforce remains widely unprepared to install, maintain and operate these systems, particularly complex software-based control platforms, as most workforce training programs still focus on traditional building automation for large commercial buildings.

This paper presents the development and piloting of curriculum for three key types of professionals:

- Technicians (trade-level): installing and maintaining modern high-performance HVAC systems and controls
- Programmers (undergrad-level): developing and implementing advanced controls
- Engineers and energy professionals (undergrad/grad-level): managing and evaluating system performance

We share details of the material developed including training videos, open-source software, instruction manuals. We also present the results of a pilot implementation of the training materials with real students.

Introduction and background

The development of advanced control solutions for commercial building HVAC systems has seen a transformation over the past decade, powered by the cost reduction of connected, IP-based edge computing hardware, proliferation of highly flexible and scalable communication and data transfer interfaces such as RESTful application programming interfaces (APIs) (Yefi, Menon and Eicker 2024), and most recently artificial intelligence (Blayo et al. 2025). In the large commercial building space, software-based optimization solutions are leveraging data-rich building automation systems (BAS) often stewarded by dedicated on-site staff or building operators via continuous commissioning activities or through ad hoc, work order based systems. These applications have become more commonplace and are now being prototyped across multiple building controls software platforms (Mishra et al. 2020; Ham et al 2023; Campbell 2025) and in some cases being offered by BAS OEMs as cloud-based offerings (Baumann, 2023). Staffing in large commercial building operations may include a certified sustainability manager and a dedicated building operator or stationary engineer. These staff members may either have university-level qualifications or may be associated with a trades organization such as the International Union of Operating Engineers, which centralizes training and certification programs and thus is better equipped to disseminate up to date curriculum on relevant emerging technologies. (IUOE 2025)

Small to medium commercial (SMC) buildings, however often have smaller equipment, very-low data availability and unless managed by a property management organization, little to no dedicated staffing for facilities management. As a result, the control solution space for this building type is less developed and the user base for such technologies is less clearly defined. For those working in SMC, either HVAC contractors or building facilities managers, the workforce is offered a haphazard, fragmented network of training resources, often offered by state energy office or utility-funded workforce training programs (SCE n.d.; Urban Green Council, 2025), or directly by OEMs targeted at their distributor network (Carrier University n.d.; Daikin Applied n.d.).

The need for a trained workforce is growing as states like California set increasingly aggressive performance targets (IMT 2026) and high-performance HVAC systems installation goals (Newsom 2022) in which SMC buildings will need to play an essential part. In order to address the gaps identified, a key component of a recently-concluded project funded by the California Energy Commission (CEC) focused on developing resources for target users including open-source software and curriculum development for 3 types of professionals:

- Technicians (building trades-level): installing and maintaining modern high-performance HVAC systems and controls
- Programmers (university-level): developing and implementing advanced controls
- Engineers and energy professionals (university-level): managing and evaluating system performance

Project overview and curriculum development

The HP-FLEX project (Paul et al. 2025a) ran from 2020 to 2026 with the primary objectives being:

- Test and demonstration of an open-source, integrated, model predictive control (MPC) system for load flexibility of high-performance HVAC systems, such as heat pumps. The solution should reliably and cost effectively respond to grid signals to minimize cost and grid impacts while optimizing electric demand and comfort according to occupant preferences.
- Develop educational curricula to train the next generation of engineers and technicians, to help promote the large-scale deployment of replicable, demand-flexible high-performance HVAC systems installations in small to medium sized commercial buildings, and to increase benefits to both individual building owners and the distribution grid compared to standard HP installations.

For objective 1, the HP-FLEX software was developed and deployed across 6 sites, 4 of 6 sites required heat pump procurement and retrofit. Thanks to an existing relationship with UC Davis, the research team obtained access to the UC Davis Smart Home, for curriculum development. The process of recruiting sites, overseeing HVAC system installation, deploying the control software and assessing performance was a multi-disciplinary effort, an element of which was captured in the university level curriculum and outcomes.

For objective 2, the curriculum development was broken out into 2 main tracks, building-trades and university-level. The building trades tracks were intended for HVAC technicians and covered the fundamentals of high-performance HVAC technology, and best practices in installation and maintenance. The building trades track was led by the project team at the Building Efficiency for a Sustainable Tomorrow (BEST) Center. LBNL has been a direct partner with the BEST Center for over eight years, offering workshops for community college instructors from around the U.S. and throughout California. The university-level tracks are intended to cover the optimization and performance assessment of the HP-FLEX controls and were carried out by the research team, piloting modules and tutorials via 2 project-based learning courses at University of California, Davis.

Building trades track

The workforce training curriculum developed by BEST as part of this project serves as an important technology transfer mechanism, by exposing teachers and the future engineering and technical workforce to the concepts of heat pump fundamentals, sizing, installation, maintenance and control. The BEST center's outline for curriculum, including main sections and underlying modules are outlined in Table 1 below. All sections are targeted for HVAC or refrigeration technicians, general repair personnel, technical school students and meant to be completed on a computer or tablet device.

Table 1: Summary of major sections and modules found in building trades-level track

Section	Module	Duration
1 – System Design Strategies	Load Calculation Tools and Software Overview	1 hour
	Building Envelope Upgrades & Changes	
2 – Installation Overview	System Operation Overview	3 hours
	Building and Site Assessment for Optimum Performance	
	Light Commercial Split System HVAC Installation	
	Light Commercial Rooftop HVAC Installation	
	Importance of Airflow to System Operation	
	Duct & Register Design for Optimal Comfort & Humidity Control	
3 – Maintenance & Service Overview	Planned Preventative Maintenance & System Operation	1 hour
	System Operation Parameters	
4 – Refrigerant Safety & A2L Refrigerant Overview	Properties of Refrigerants and Their Incompatibility with the Atmosphere	1 hour

University-level tracks

The primary objective in building university-level energy education was bridging the gap between theoretical knowledge and real-world application. Students typically learn HVAC principles through simplified models in a lecture setting and controlled laboratory exercises, but rarely encounter the complexity of actual building systems with their inherent variability, data quality issues, and operational constraints. The university level modules were broken out into two separate sections: Software deployment and Living Lab.

Software deployment. These modules address the aforementioned gaps by providing students with an authentic experience using the HP-FLEX open-source software. HP-FLEX's software packages supporting the MPC algorithm are published online in a Bitbucket repository[1]. The package includes implementation guidelines, tutorials for semantic-driven MPC[2] (Paul et al. 2025a) development and testing, as well as a building simulation platform for testing and validation via the BOPTEST framework (Blum et al 2021; Paul et al 2025b) to validate the MPC algorithm prior to deployment.

The educational modules are structured around 6 learning areas that reflect the nature of building energy systems and the multidisciplinary skills required for professional practice, starting from the concept of grid-interactive building (Goetzler et al. 2019) to the deployment and operation of MPC. Learning areas for each set of activities are listed below:

1. Understanding the overall concept of grid-interactive building HVAC systems and controls (e.g. MPC) and how they work
2. Establishing the entire deployment process based on the target site's building energy system
3. Establishing the MPC controller using the open-source MPC software developed by the research team
4. Implementing the MPC controller in both virtual (BOPTEST) and a real building and monitoring continuous operations with ongoing troubleshooting
5. Establishing best practices for the ongoing operation of the product, including computational error handling, communication outage management, and emergency planning

Living laboratory. These educational modules address the aforementioned gaps by providing students with real field demonstration data for performance measurement and verification (M&V) of the technology. The students were provided with key information on one of HP-FLEX’s deployment sites and a custom set of data analysis and visualization scripts. The educational modules are structured around 3 learning areas that reflect the nature of building energy systems and the multidisciplinary skills required for professional practice:

1. Understanding the overall concept of grid-interactive building HVAC systems and the deployment of high-performance HVAC controls in a California policy context
2. Develop skills in best-practice M&V methodologies for HVAC operations, learning to collect, validate, and analyze building performance data.

[1] bitbucket.org/berkeleylab/hp-flex-mpc

[2] Semantic models, such as the Brick Schema or ASHRAE s223, can accelerate the adoption of MPC applications by providing consistent and structured naming conventions which streamline data normalization, and application configuration

3. Learn how to use Python and other visualization tools to demonstrate to stakeholders the value of HP-FLEX as a solution

Pilot implementations

Building trades track

The workforce training curriculum developed by BEST were built in Articulate Storyline 360[3]. Key design principles include:

- no autoplays, students must actively engage to advance,
- quiz retries reset completely so returning students get a fresh attempt, and learners can explore content non-linearly.
- all modules carry audio narration, closed captions, and optional depth.
- supplementary content like psychrometrics is available to learners who want to go further but is not on the required breadcrumb trail.

A 360-degree virtual tour inside an actual Carrier 8-ton RTU was highlighted as the standout feature, a rare opportunity for students to explore equipment internals that are rarely accessible in training environments due to safety, liability, and institutional constraints. Figure 1 shows the entry screen for the Commercial Load Calculations module, which sets one of the HP-FLEX sites as the learning environment before walking students through the building. Figure 2 illustrates one of the module's interactive assessments: a drag-and-drop quiz in which students must identify all items in a kitchen that contribute to the heat load combining visual recognition with conceptual application.

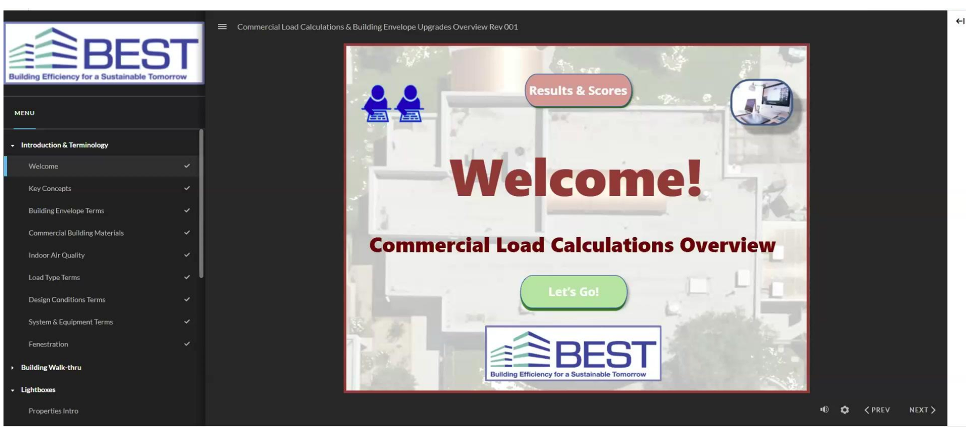

Figure 1: Load Calculations module welcome screen for module based on field site

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3 https://www.articulate.com/360/storyline/

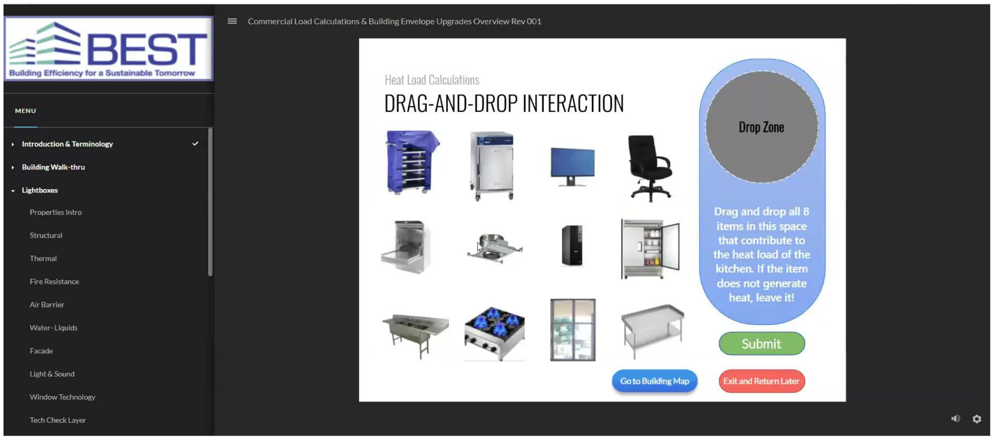

Figure 2: Drag-and-drop heat load quiz from the Commercial Load Calculations building walkthrough

The modules are intentionally foundational, serving to optimize student preparation for hands-on instruction rather than acting as a replacement for it. By front-loading conceptual knowledge through online interactivity, valuable lab time is preserved for practical activities instead of being consumed by basic terminology. In addition, students who struggle with a concept in the lab can revisit the module to explore it from a different perspective. The modules were finalized in June 2026, with a train-the trainer workshop held on June 5. The June 5 workshop was the third installment of BEST Center's "Creating Tomorrow's Workforce Today" webinar series, serving as the public debut of the HP-FLEX curriculum to community college faculty and workforce development professionals.

Attendees represented a mix of active community college faculty, former instructors now in workforce development roles, workforce development program managers, and senior practitioner-instructors with extensive field backgrounds. Multiple attendees expressed immediate intent to deploy the modules at their institutions, indicating they would begin with the free web version as a preview before pursuing the formal learning management system package integration, which is consistent with the rollout approach described by the development team. At least one attendee offered to beta test the modules before full publication. The mentioned that the courseware is free generated enthusiastic reactions from multiple participants. For community college programs operating under tight professional development and curriculum budgets, the zero-cost access model removes a significant adoption barrier and should be a prominent element of all dissemination messaging going forward.

Finally, several attendees signaled paths to additional institutions beyond those directly represented at the summit, including requests to share modules with colleagues at other colleges and expressions of intent to introduce the curriculum to their broader professional networks. This organic dissemination pathway (from early adopters to their institutional peers) is consistent with how curriculum resources spread through workforce development networks and should be supported by ensuring the web preview and contact information are easily shareable.

University-level tracks

Software deployment. The first class, EME 185 was a 6-month long senior design course running across 2 academic quarters. These students were tasked with working through the tutorials provided in the HP-FLEX open source software repository and carrying out a real field demonstration. The students were able to leverage an existing HVAC system (mini split system) and control infrastructure (thermostat with Sensibo wireless controller[4]) found in the UC Davis Smart Home[5], a fully operational home doubling as a research lab, to develop their MPC algorithm, perform system identification and develop their own test schedule to carry out a lean version of the HP-FLEX software stack in part enabled by Google cloud services available to the students through their university[6]. The site where the implemented software was deployed is shown in Figure 3 below. The students were able to run tests across a set of weeks and also run a set of failure scenarios in order to develop and assess risk management strategies of their deployment, a critical planning mechanism when deploying in the field.

Figure 3: UCD Smart Home, site for EME 185 software deployment for student-led project

Living laboratory. The second course, ABT 212, ran through the spring academic quarter. The research team partnered with UC Davis faculty to integrate the HP-FLEX project into the project-based class: "ABT 212: A Path to Zero Net Energy: A Hands-on Approach." The team provided a real-world case study to a student group and offered guidance and support throughout the class, including:

- Initial kick-off meeting providing HP-FLEX technology introduction and M&V project overview
- Weekly check-in meetings for ongoing student support and progress discussions
- Conclusion meeting after students' final presentation and poster sessions in the course

The case study focused on one of the HP-FLEX deployment sites (office building at UC Davis), and featured actual building performance data and control system operations. To facilitate a hands-on learning experience, the HP-FLEX team provided students with access to measurement and verification (M&V) datasets, comprehensive guidance documentation, and training on M&V methodologies. The team also provided on-demand technical support, offering expert guidance on

[4] support.sensibo.com/getting-started/what-is-sensibo/
[5] energy.ucdavis.edu/smarthome/
[6] edu.google.com/resources/customer-stories/uc-davis-capstone/

the hardware and control system, data structure, and analytical methods, to help students effectively work with and analyze the field data.

The students showcased significant learning outcomes, as evidenced by their ability to conduct advanced data analysis, develop statewide impact models, and provide policy recommendations informed by actual performance data. They successfully completed tasks that aligned with best practices in M&V methods, such as matched-day analysis, seasonal performance evaluation, and scaled that to a statewide impact analysis. The main deliverable package submitted by the students included

- technical report providing comprehensive HP-FLEX performance analysis
- slide presentation
- research poster (see Figure 4)

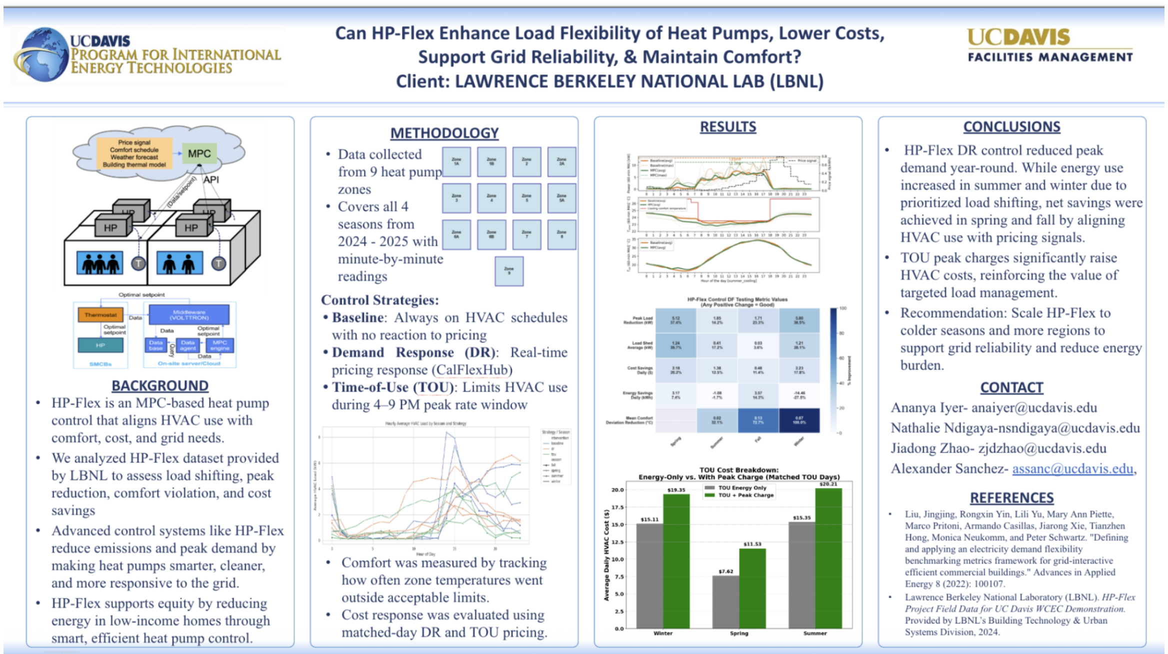

Figure 4: Final poster presentation for living lab student-led project team

For interested parties, Table 2 summarizes the resources developed across the 2 tracks, along with links to the resources.

Table 2: Summary of major sections and modules found in building trades-level track

Resource	Link	Notes
Building trades training modules	https://bestctr.org/curricula/	Online only modules are found in the link provided, however this material is available to be integrated into LMS

		platform upon request
MPC software deployment package	https://www.osti.gov/biblio/code-158609 (Kim and Ham, 2024)	Software packages include MPC algorithm framework as well as tutorials
M&V and data analysis package	https://tinyurl.com/4b3m96yv	A subset of the HP-FLEX building performance data is available here to perform M&V activities

Discussion

Lessons Learned

The building trades curriculum development and workshop confirmed key assertions of underserved SMC market sector and value of asynchronous, 360- degree learning format. When asked about current tools for heat pump instruction, workshop participants offered few examples, confirming the initiative's premise that SMC training remains a significantly underserved domain. The diverse background of attendees, comprising veteran practitioners with decades of experience who have transitioned into education, underscores a systemic workforce hurdle: while deep technical expertise exists in the field, it has yet to be codified into organized and reachable instructional frameworks.

Attendees with prior experience using 360-degree virtual tools in their own teaching independently validated the approach, confirming that production barriers are manageable with institutional instructional technology support and that virtual walkthroughs provide value particularly as makeup options for students who miss hands-on sessions and as lecture reference aids. This agreement across participants strengthens the case for the format and suggests the curriculum is entering a receptive environment rather than introducing an unfamiliar format.

Both UC Davis EME185 and ABT 212 pilot implementations provided valuable insights into the practical aspects of 1) hand-off of internally developed software tools to a bachelor-level group of students for intention of deployment and 2) transforming M&V field data into effective educational resources. Through direct collaboration with students over the winter and spring quarters, several key challenges and success factors emerged that will inform future implementations.

Navigating real-world data complexity. One of the most significant learning experiences in EME 185 was students' first encounter with live field data from the UC Davis Smart Home HVAC system. Unlike the curated datasets typically used in coursework, the field data exhibited characteristics that required substantial pre-processing: missing values resulting from communication dropouts between the Sensibo controller and the cloud API, signal noise from sensor variability, and timestamp inconsistencies that complicated time-series alignment. Students who had previously worked only with clean, well-structured datasets were confronted with the reality that a significant portion of real deployment work involves data validation and pipeline management rather than algorithm development alone. This experience proved to be one of the most instructive aspects of the course.

Bridging the gap between theory and field conditions. A recurring theme throughout the EME 185 project was the contrast between how HVAC systems behave in simplified models and how they behave in practice. Students initially approached the MPC development task including the identification of physical model parameters (known as system identification) with assumptions drawn from idealized models, expecting smooth, predictable thermal responses and stable equipment behavior. The actual data from the Smart Home mini-split system revealed a more complex picture: variable thermal loads driven by solar gain and occupancy, equipment cycling behavior that complicated steady-state assumptions, and weather-dependent performance variation that required students to revisit and recalibrate their modeling approach and parameter estimations. This gap between textbook expectations and field reality shows the importance of bridging the theoretical example to the real-world application.

Understanding physical systems through hardware interaction. Working directly with the physical infrastructure of the UC Davis Smart Home, including the mini-split HVAC unit, the Sensibo wireless controller, and the associated sensor network, gave students a tangible understanding of the physical systems underlying the data streams they were analyzing. Understanding how a control signal issued by the MPC algorithm travels through the cloud API, is received by the Sensibo controller, and ultimately commands the mini-split compressor provided a concrete mental model that deepened students' interpretation of system response data. This embodied understanding of the hardware layer is difficult to replicate in simulation alone and represents one of the distinctive pedagogical advantages of a living lab deployment context.

Diagnosing and responding to system failures. A particularly valuable component of the EME 185 course was the deliberate inclusion of failure scenario design. Students designed and executed tests in which components of the control system were intentionally disrupted, simulating communication outages between the Sensibo controller and the cloud, API authentication failures, and MPC software errors. Students were required to develop structured risk management and contingency response strategies. This exercise shifted students from passive system observers to active system stewards, requiring proactive thinking about resilience, fault detection, and recovery procedures. The ability to diagnose unexpected system behavior and formulate a structured response is a critical professional competency that engineering curricula rarely address explicitly, and the live deployment context made this learning concrete and consequential in a way that purely simulated environments cannot fully replicate.

Team role differentiation and collaboration. The EME 185 project team naturally differentiated into functional sub-roles over the course of the project, including responsibilities for software deployment and API integration, system identification and MPC model development, MPC algorithm implementation, failure scenario design, and results documentation. Teams that established clear role ownership early tended to make more consistent progress and produce more coherent final deliverables, while ambiguity in responsibility at integration points. For example, the handoff between the data pipeline and the MPC input layer was a recurring source of delay. Future implementations should incorporate an explicit role-mapping exercise at project kickoff, helping students identify individual strengths and establish accountability structures that reflect the multidisciplinary nature of real building energy deployment projects.

Systems thinking and software architecture literacy. Perhaps the most distinctive educational outcome of the EME 185 deployment track was the development of systems thinking across the complete HP-FLEX technology stack. Systems thinking is a holistic way to investigate factors and interactions that could contribute to a possible outcome. Re34ather than treating each architectural layer, including physical sensors and actuators, wireless communication and cloud APIs, and MPC optimization as a black box, students were required to understand how data and control signals flow across layer boundaries, how failures at one layer propagate to others, and how hardware-level design decisions constrain algorithmic performance. A closely related outcome was students' growing ability to navigate the HP-FLEX open-source codebase, which was developed for research rather than education and thus presented the realistic challenges of interdependent modules, incomplete documentation, and non-obvious design choices. Together, these outcomes represent some of the most professionally relevant competencies that field demonstration-based education can provide, and ones that are rarely achievable in courses that treat sensing, networking, and optimization as separate disciplinary domains.

Project scope management. Clear definition and adjustment of project scope proved critical for ensuring deliverables are completed within academic time constraints. Flexibility in scope design allowed accommodation of emerging student interests while maintaining realistic expectations for what could be accomplished during the quarter system timeline.

Communication structure. Weekly check-in meetings were essential for tracking progress and addressing student needs. These meetings enabled responsive support. One example is when time-of-use pricing information was initially omitted from data sharing but quickly provided after students identified this gap during an economic analysis discussion. This structured communication prevented delays and ensured students had access to all necessary information.

Foundational knowledge requirements. Students without building energy analysis experience needed a more comprehensive background on M&V principles (such as match-day analysis, and change-point-model) at the project beginning. While the modules focused on project-related data were successful, a more comprehensive overview of M&V industry practices and state-of-the-art practices would provide essential context for students entering this field and help them understand the broader professional landscape.

Conclusion

The results and discussion effectively demonstrate the value across both curriculum tracks in addressing the gaps in widespread availability of SMC-specific education for HVAC installation maintenance and control. However, there is still much more work required to fold in the lessons learned described herein to ensure the modules are able to effectively scale and reach the intended audience. The modules and software packages are publicly available (we summarize location of material in Table 2) for online only consumption or integration with existing LMS platform systems. Longer term, the research team will be focused on disseminating these resources in appropriate venues, including workforce development focused conferences and webinars.

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