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Permalink

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Journal

Energy and Buildings, 344

ISSN

0378-7788

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Publication Date

2025-10-01

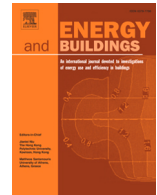
DOI

10.1016/j.enbuild.2025.115917

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Experimental validation of a co-simulation architecture for modeling whole-building and detailed electrical distribution performance

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ARTICLE INFO

Keywords:

Building performance simulation

Electrical distribution systems

Co-simulation

Model validation

ABSTRACT

This article presents an experimental validation of a co-simulation architecture for simultaneously modeling whole-building energy performance and detailed building electrical distribution system performance. The co-simulation architecture consists of a whole-building energy model (EnergyPlus®) embedded within a Modelica-based building electrical distribution system library called the Building Electrical Efficiency Analysis Model (BEEAM) using the Functional Mock-up Interface standard. We validate the model using experimental data collected at a full-scale test cell within Lawrence Berkeley National Laboratory's FLEXLAB® facility. We show that the co-simulation model accurately predicts the electrical, mechanical, and thermal performance of the test cell for typical loads with both an AC and a DC electrical distribution topology.

1. Introduction

Recent developments in electrical distribution technology for buildings, in particular direct current (DC) distribution, have driven significant research and industry interest in modeling the performance and efficiency of building electrical distribution systems [1–6]. Electrical losses within a building's electrical distribution system produce heat gains within the building, affecting the building's heating and cooling load and the performance of heating ventilation and air conditioning (HVAC) systems. Recent research, including by contributing authors, has begun to explore the interaction among building electrical distribution, HVAC systems, and other building systems using co-simulation techniques [7–10]. However, to date, little research has validated the accuracy of such co-simulation models.

Previously, contributing authors and others developed a Modelica library called BEEAM for the detailed simulation of building electrical distribution systems based on harmonic power flow [11,12] and a co-simulation architecture that combines the library with the EnergyPlus® software for whole-building energy simulation [9]. In this article, we present an experimental validation of the co-simulation architecture described in that work [9]. As mentioned in [9], electrical distribution losses are rarely incorporated into whole-building energy models and

tools like EnergyPlus. Few tools currently exist which accurately predict such losses, and those that do are not typically designed to facilitate incorporation into whole-building energy models. Co-simulation of thermal and electrical loads in buildings can improve the accuracy of the estimated loads and losses, mainly by more precise modeling of the magnitude of heat gains from electrical devices. For example, co-simulation can capture the effect of relocating the power conditioning (power supply) module in a different thermal zone (unconditioned space) than the end use equipment (conditioned space) on building cooling and heating demand. This co-simulation capability can strengthen the quantification of auxiliary benefits due to system and topology improvement, which can subsequently lead to better design practices.

The importance of validating software models for building energy performance has been recognized for several decades [13]. A large body of work has addressed the validation of building performance simulation (BPS) software, focusing on software that models the thermal performance of buildings, including that of HVAC systems [14–17]. In the context of whole-building energy models, ASHRAE has adopted and formalized validation best practices in ANSI/ASHRAE Standard 140 [18]. BPS software such as EnergyPlus is subjected to regular ongoing validation based on industry standard methods as new versions are developed [19,20].

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<https://doi.org/10.1016/j.enbuild.2025.115917>

Received 4 October 2024; Received in revised form 8 May 2025; Accepted 24 May 2025

Available online 30 May 2025

0378-7788/© 2025 Published by Elsevier B.V.

In contrast, building electrical distribution system models (as opposed to utility-scale models) have been only sparsely validated. Aspects of the Modelica Buildings Library [7] have been validated experimentally [21,22], although not the electrical component models. Santos et al. [23] demonstrated good agreement among several building electrical distribution models, including one based on harmonic power flow, and Othee et al. [11] executed a series of laboratory experiments to validate the Modelica library leveraged in this work. Prior work by contributing authors [9] included a small-scale validation of the proposed co-simulation architecture, but identified the need for more comprehensive validation.

This article provides a building-scale validation of the co-simulation architecture described in [9]. We co-simulated a traditional, alternating current (AC) distribution system and a DC distribution system with a two-zone energy model representative of an open office area within a typical office building, and we validated the models using experimental data collected at Lawrence Berkeley National Laboratory's FLEXLAB[®] facility [24]. The remainder of the article is organized as follows: Section 2 describes the experimental design, models, and validation procedure; Section 3 presents the validation results; Section 4 discusses the model accuracy, lessons learned from the validation experiments, and implications for future research; and Section 5 provides conclusions.

2. Methods

The purpose of this research was to validate the ability of the co-simulation architecture of [9] to accurately predict both the electrical and thermal energy performance of an entire building. In the co-simulation architecture, BEEAM models the electrical distribution system while EnergyPlus models the building thermal performance and the HVAC systems. Calculated electrical distribution system loads are an output from EnergyPlus and an input to BEEAM; calculated electrical distribution system losses are an output from BEEAM and an input to EnergyPlus. The co-simulation architecture allows more comprehensive and complex modeling of system performance than either software used alone. For example, the architecture permits other data (schedules, zone temperatures, HVAC loads, voltage, current, and the like) to be exchanged between the two modeling engines, but these capabilities were not used in the validation study.

The study consisted of four experiments: two to calibrate a whole-building energy model of the test cell and two to validate a pair of co-simulation models representing typical AC and DC distribution topologies. The validation experiments compared the accuracy of the proposed co-simulation approach to the accuracy of modeling the electrical and thermal loads with EnergyPlus.

2.1. Experimental design

FLEXLAB is a whole-building test facility for studying integrated building systems, including HVAC, lighting, windows, building envelope, controls, and plug loads, in any combination [24,25]. Integrated systems can be tested using custom configurations and varying load conditions. The facility is densely instrumented to monitor essential performance data. FLEXLAB has four testbeds, each of which consists of two identical side-by-side test cells. Each individual test cell has a configurable glazed south facade typical of a commercial office building. All other test cell exterior surfaces are highly insulated (nearly adiabatic), such that the test cell resembles a single perimeter zone within a large building. Each test cell has a dedicated air handling unit (AHU) with hot water coil, chilled water coil, economizer, and supply fan. The test cells are designed and calibrated to achieve a high level of consistency between cells and repeatability between experiments, enabling detailed evaluations of alternative building systems under controlled conditions. FLEXLAB provides device-level energy measurement and high-accuracy instrumentation for other physical quantities related to building performance (temperature, humidity, and heat flux).

Table 1
Time periods of experimental data.

Experiment	Data begin	Data end
Calibration 1	2020-10-30 00:00 PDT	2020-11-04 15:00 PST
Calibration 2	2020-11-04 16:45 PST	2020-11-06 15:00 PST
AC Experiment (Low Power)	2020-11-11 10:30 PST	2020-11-11 17:00 PST
AC Experiment (Medium Power)	2020-11-12 14:30 PST	2020-11-13 11:30 PST
AC Experiment (High Power)	2020-11-13 12:00 PST	2020-11-16 08:00 PST
DC Experiment (High Power)	2020-11-17 18:00 PST	2020-11-20 16:00 PST
DC Experiment (Low Power)	2020-11-23 11:30 PST	2020-11-25 08:45 PST
DC Experiment (Medium Power)	2020-11-25 09:30 PST	2020-11-30 08:00 PST

We conducted all four experiments in FLEXLAB test cell 3B (Fig. 1). The cell has dimensions of 6.1 m by 9.1 m, and gross floor area of 55.8 m² (600 ft²). The cell has a 2.7 m interior ceiling of suspended acoustic tiles, above which is a plenum with ducted supply and return air for the conditioned space. The test cell roof is slightly sloped; its height varies from 4.2 m to 4.5 m. The primary test chamber adjoins the south facade. An insulated wall partitions this chamber from the cell's north wall, electrical room, and mechanical room, such that the conditioned zone has effective dimensions of 6.1 m by 7.6 m, and floor area of 46.5 m² (500 ft²). Batts of denim insulation above the ceiling tiles isolate the plenum from the conditioned zone, and 10 cm (4 in) of polyisocyanurate foam insulation isolates the cell floor from the underlying concrete slab.

Test cell 3B has the highest number of embedded temperature and heat flux sensors out of all FLEXLAB test cells, making it an ideal laboratory for model validation studies. The thermal characteristics of the cell components (envelope, windows, interior walls) are well-documented, and a well-calibrated EnergyPlus model of the envelope is available from a prior study [19]. During the study period, the data collection system recorded energy for each electrical circuit; interior temperatures in the plenum and conditioned zone; AHU supply and return air temperatures, airflow, and delivered heating and cooling; and ambient weather conditions including temperature, direct irradiance, and diffuse irradiance.

Fig. 2 displays a timeline of the four experiments, and Table 1 lists the start and end times of the usable data obtained from each experiment. Momentary power failures during the AC and DC experiments disrupted the HVAC system controls, resulting in deviations in system behavior and zone temperature. We have excluded these periods from the validation data set, so the data for the AC and DC experiments are discontinuous. The study included four experiments:

1. *Calibration 1*: Free oscillation (no HVAC) for envelope calibration
2. *Calibration 2*: Conditioned operation with fixed loads for AHU calibration
3. *AC Experiment*: Co-simulation of AC distribution system with plug loads and lighting
4. *DC Experiment*: Co-simulation of DC distribution system with plug loads and lighting.

During all four experiments, the test cell's south facade was covered with rigid foam insulation to reduce heat transfer and eliminate heating from direct solar gain. Therefore, because the test cell was unoccupied, lighting and electric equipment provided the only internal heat gains to the conditioned zone and plenum. During the second calibration experiment as well as the AC and DC experiments, the test cell's AHU provided mechanical cooling. (The AHU economizer was disabled for the duration of the study.) Six consumer-grade oscillating fans circulated air within the zones: four in the conditioned space (operated during all experiments) and two in the plenum (operated during the AC and DC experiments only). The purpose of these fans was to ensure well-mixed spaces, consistent with EnergyPlus's default simulation settings.

Loads consisted of (LED) lighting fixtures, programmable DC load banks (or plugs), the circulation fans, and miscellaneous data collection equipment. Load configuration, including the power converters supplying the loads, varied by experiment. Table 2 summarizes the load configuration for each experiment, and Figs. 3–5 display the one-line diagrams

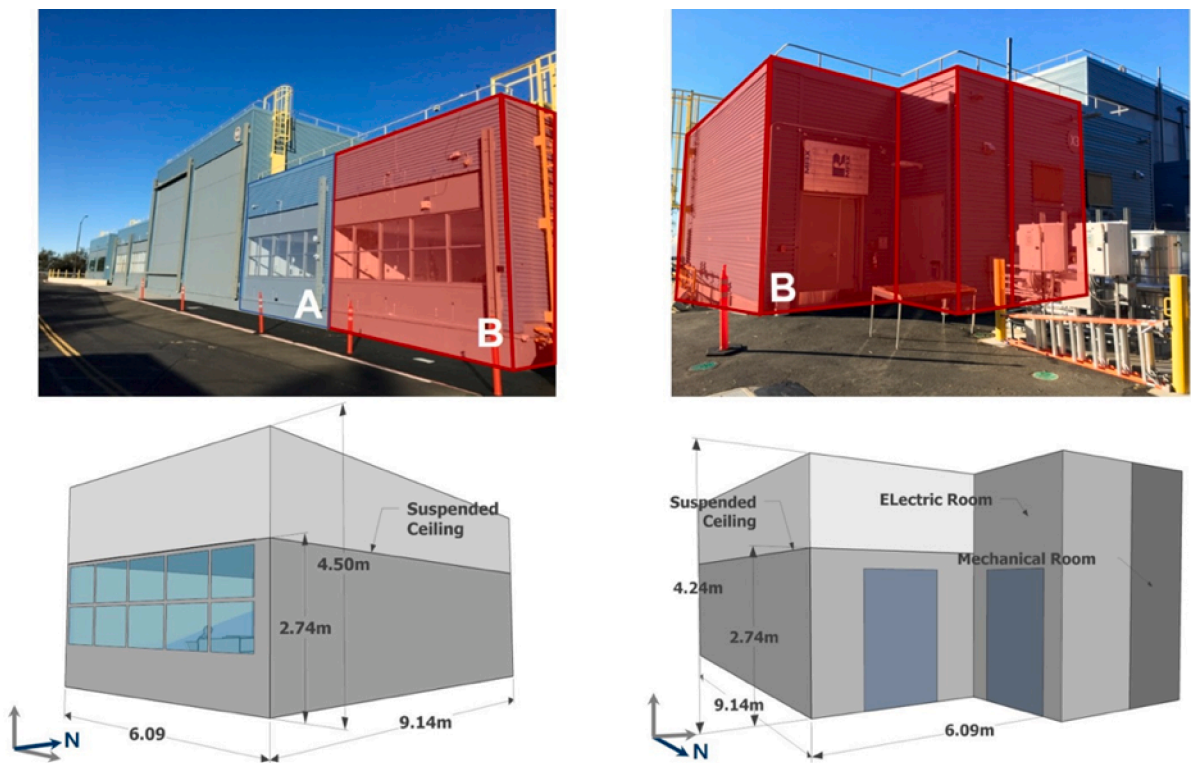


Fig. 1. Photographs of FLEXLAB test cell 3B with illustrated dimensions. Graphic from [[19], Fig. 14], with photographs by FLEXLAB Staff, LBNL; reused with permission..

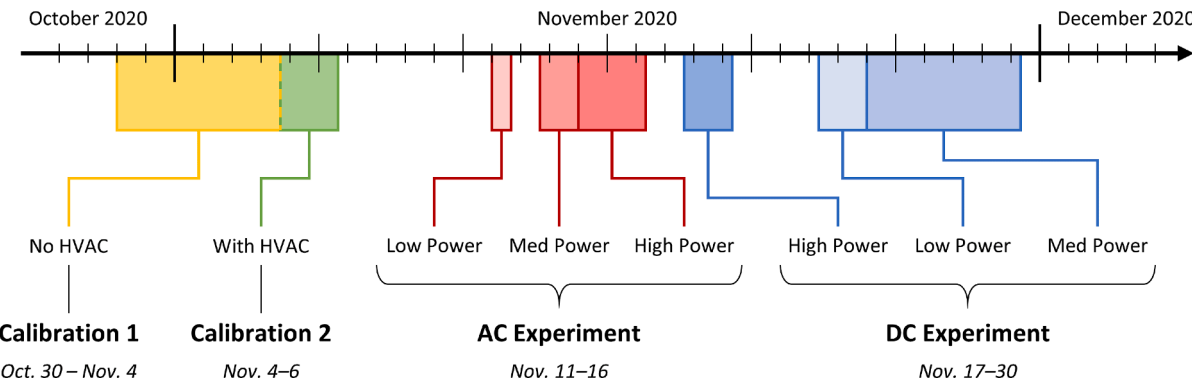


Fig. 2. Timeline of model calibration and validation experiments.

Table 2
Electric load configuration during experiments.

Device	Category	Location	Qty	Calibration	AC Exp.	DC Exp.
2' × 4' AC-input LED troffer	Load	Conditioned zone	6		✓	
2' × 4' DC-input LED troffer	Load	Conditioned zone	6			✓
Programmable DC load bank	Load	Conditioned zone	6	✓	✓	✓
Oscillating circulation fan	Load	Conditioned zone	4	✓	✓	✓
Oscillating circulation fan	Load	Plenum	2		✓	✓
Misc. data collection equipment	Load	Conditioned zone		✓	✓	✓
AC-input LED troffer integrated driver	Converter	Plenum	6		✓	
550 W AC/DC computer power supply	Converter	Conditioned zone	6	✓	✓	
Central AC/DC converter/power hub	Converter	Plenum	1			✓

for each experiment, including loads and power conversion equipment. (Wiring is not shown in these one-line diagrams; for physical wiring configuration see the expanded one-line diagrams available from Frank et al. [12].)

During the two calibration experiments, the BK Precision 8500B programmable DC load banks and their associated Seasonic FOCUS PX-550 AC/DC power supplies provided internal heat gains to the conditioned

zone. The lights remained off. Power-over-Ethernet networked single-board computers interfaced with the load banks to provide remote control. The programmable loads were placed on simple desk surfaces at a height of 0.76 m (30 in) above the floor and programmed to draw 55 W each. Losses from the AC/DC power supplies, circulation fan load, and miscellaneous load from the control and data collection equipment also added heat to the conditioned zone.

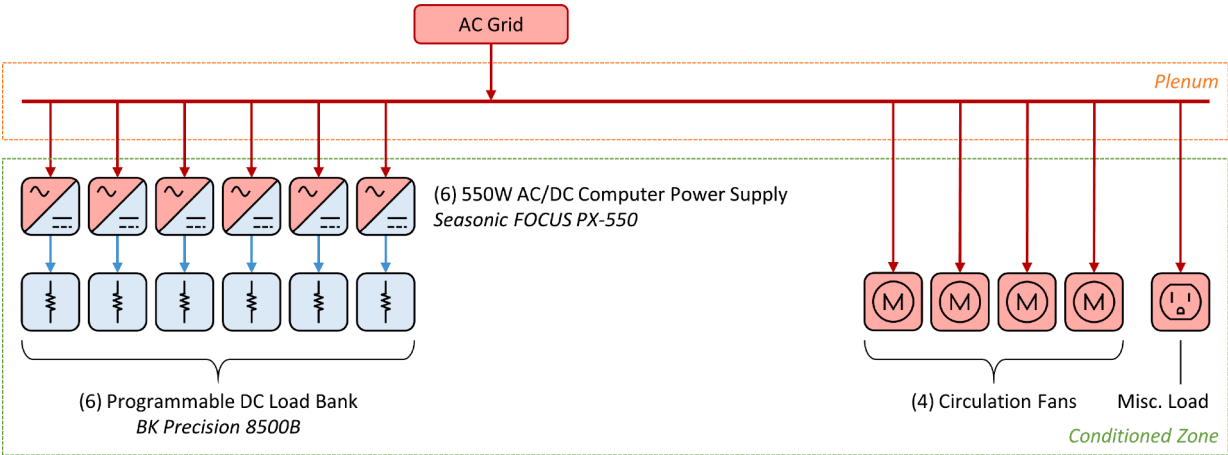


Fig. 3. Electrical one-line diagram for calibration experiments 1–2.

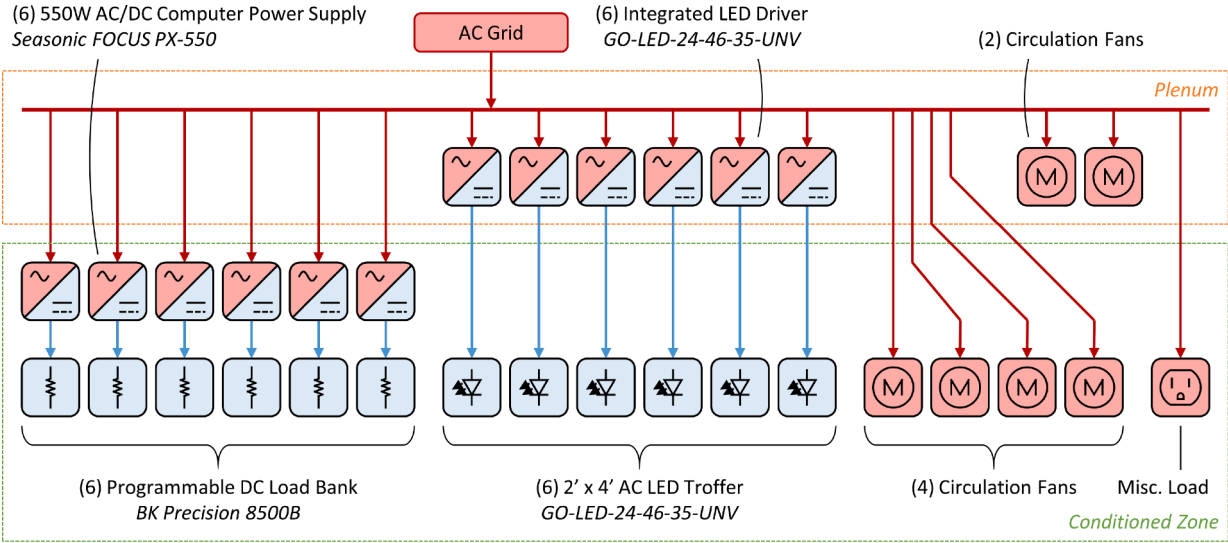


Fig. 4. Electrical one-line diagram for the AC experiment.

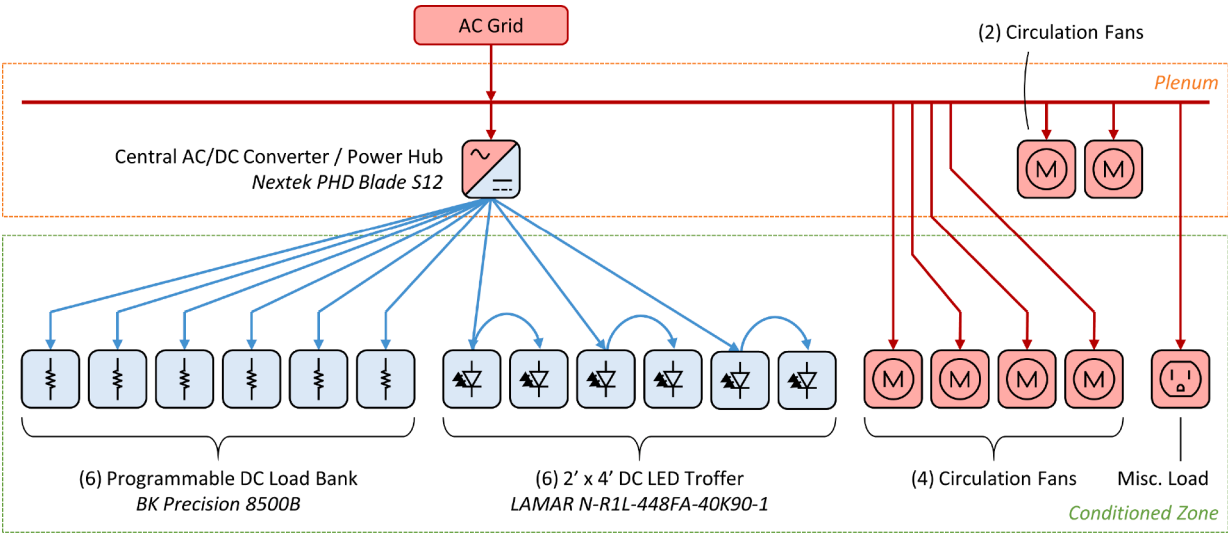


Fig. 5. Electrical one-line diagram for the DC experiment.



Fig. 6. Test cell experimental setup for AC and DC experiments. Photograph by Jordan Shackelford, LBNL; used with permission.

The first calibration experiment consisted of a free oscillation period, during which we disabled the AHU. Free oscillation allows calibration of the whole-building model's envelope and thermal mass parameters independent of the HVAC system [26]. During the second calibration experiment, the AHU operated to maintain the conditioned zone temperature at 20°C; this setpoint increased to 23°C during the validation experiments. The AHU operated continuously as a constant volume system, with modulating heating water and chilled water valves for temperature regulation.

During the AC experiment, the programmable DC load banks were connected as in the calibration experiments and programmed to consume 55 W, 155 W, and 225 W each during the low-, medium-, and high-power portions of the experiment, respectively. The experiment included six 2' x 4' AC-input LED troffers with integrated drivers, model GO-LED-24-46-35-UNV, recess-mounted in the drop ceiling and powered from standard 120 V_{AC} outlets. The integrated driver in each fixture was an Osram model OTi48. The lights operated at 50 %, 70 %, and 100 % output (approximately 30 W, 52 W, and 58 W each) during the low-, medium-, and high-power portions of the experiment, respectively. The data acquisition system recorded the aggregate input power of each group of loads: AC/DC power supplies, LED drivers, circulation fans, and miscellaneous loads.

For the DC experiment, we replaced the Seasonic AC/DC power supplies with a central multichannel power hub with AC/DC converter, Nextek model PHD Blade S12, located in the plenum. The Nextek PHD Blade has 12 ports and is capable of supplying up to 100 W at 24 V_{DC} per port. It accepts multiple input voltages, both AC and DC; for this experiment we operated it on 120 V_{AC}. The programmable DC load banks remained in the conditioned zone and connected to 6 ports (1 load bank per port) via #12 AWG 2-wire cables. We replaced the AC-input LED lights with driverless DC-input 2' x 4' LED troffers, LAMAR model N-R1L-448FA-40K90-1, each nominally 45 W at 24 V_{DC}. These connected to an additional 3 ports (2 lights per port), also via #12 AWG 2-wire cables located in the conditioned zone. (There was insufficient space available in the plenum for the DC cables.) The programmable load banks were programmed to consume 30 W, 60 W, and 90 W each during the low-, medium-, and high-power portions of the experiment, respectively. Due to control limitations with the Nextek PHD Blade, the LED lights did not modulate. Instead, they operated at a constant load of approximately 30 W per fixture for the duration of the experiment. The data acquisition system recorded the aggregate input power of each group of loads: the Nextek PHD Blade, circulation fans, and miscellaneous loads.

Fig. 6 shows the interior of the test cell during the AC and DC experiments. The programmable load banks and AC/DC power supplies are on the three desks (two of each per desk). In the photograph, the camera

faces southwest, and the insulation covering the south facade windows is clearly visible. The partition wall at the rear of the conditioned zone is behind the position of the camera. The lights for the AC and DC experiments are the AC-input and DC-input LED troffers, respectively. The many other cables in the photograph are due to the high density of temperature and other sensors. The rods extending from floor to ceiling are the air temperature stratification measurement “trees.” Each stratification tree has up to seven temperature sensors at varying heights in the conditioned space, with two additional sensors in the plenum above the ceiling.

2.2. Model architecture

For the validation study, we modeled whole-building energy performance using EnergyPlus 9.4.0 [27] and electrical distribution system performance using BEEAM 0.2.0-beta [12]. The BEEAM model is implemented in Modelica [28,29]. The EnergyPlus model is embedded within the BEEAM model as a functional mock-up unit (FMU), as described in detail by Frank et al. [9]. The EnergyPlus model uses a timestep of 15 min with the start and end times listed in Table 1.

Figs. 7 and 8 display the model architecture and co-simulation data exchange for the AC and DC validation experiments, respectively. End-use powers for DC lighting and plug loads originate as schedules in EnergyPlus; these powers are inputs to BEEAM during co-simulation. BEEAM calculates the associated electrical losses for the wiring and AC/DC converters in the system and passes the values back to EnergyPlus. EnergyPlus applies the losses as heat gains within the conditioned zone or plenum, as applicable. The BEEAM model includes only the DC loads with their associated wiring and AC/DC converters; the remaining electrical loads are modeled as fixed heat gains within EnergyPlus and are not part of the validation study.

The data exchange structure used in this study was designed to match the available validation data, not to demonstrate all capabilities of the co-simulation architecture. For example, Frank et al. [9] demonstrate how zone temperatures from EnergyPlus can be provided as inputs to BEEAM to modify electrical models, such as temperature-dependent resistors. Some electrical components' efficiency is temperature-dependent, including wiring and transformers [30]. However, temperature effects within building electrical distribution systems are generally small compared to the effects of variable loading. Moreover, the use of air conditioning reduces temperature variation in the validation experiments. Therefore, to simplify the analysis, temperature effects on electrical losses are neglected in the validation study. The resulting model architecture is excellent for validation but less compelling as a use case for co-simulation, as discussed in Section 4.3.

2.2.1. Whole-building model

We adapted the whole-building model from a prior model developed for an earlier experiment [19]. The existing model included architectural and electrical systems, but did not include a mechanical system. We first updated the model from EnergyPlus 8.8.0 [31] to EnergyPlus 9.4.0 [27] by importing the existing input data file into the OpenStudio Application 1.1.0 [32]. We further modified the architectural and mechanical components in the model to match the conditions of the experiments, as detailed below. (In the context of the EnergyPlus model used in this study, “architectural” components and parameters refer to characteristics related to or a function of the building's architectural design, such as envelope, massing, infiltration, and heat transfer. This is in contrast to the term “architecture” when used in the context of the co-simulation approach, where it describes the structure of simulation and data exchange.)

The existing whole-building model geometry includes both test cells 3A and 3B (Fig. 9). Mechanically, cell 3B contains five thermal zones, four of which are visible in Fig. 9. The plenum, which lies above the conditioned zone (FlexLab-X3-ZoneB) and temporary zone (FlexLab-X3-ZoneB-Temp), is the fifth zone. For the simulations, the air temperature

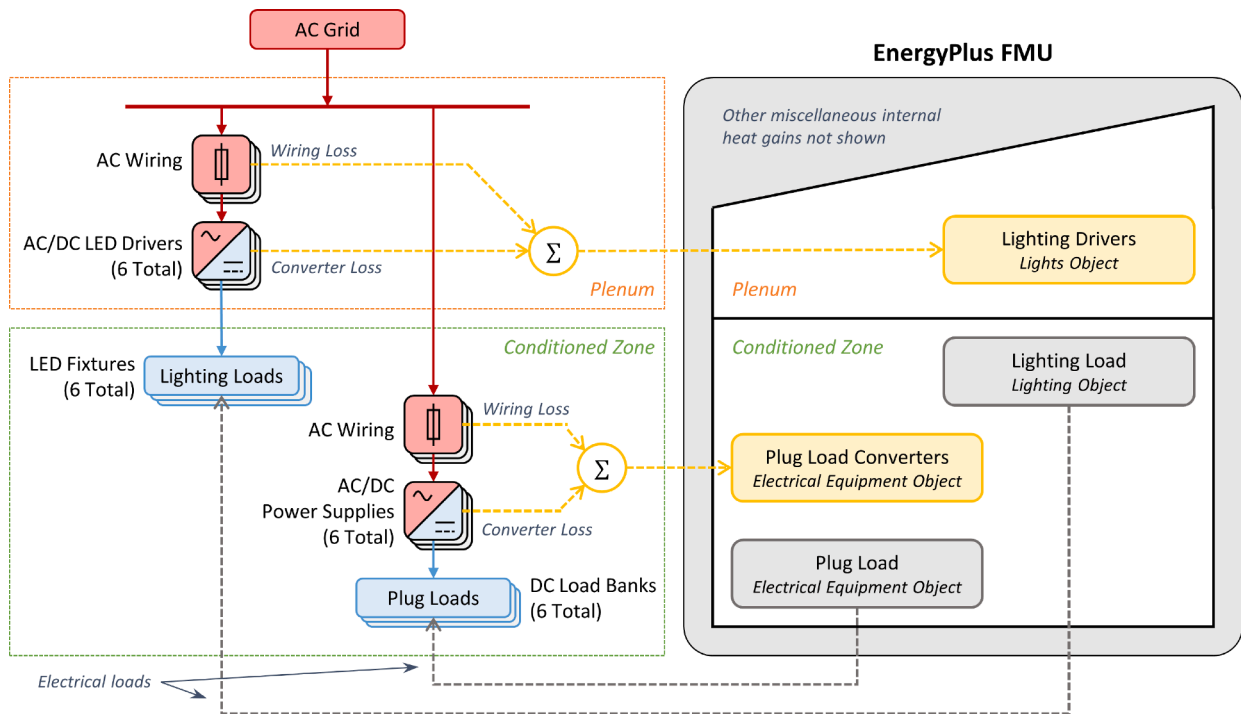


Fig. 7. Co-simulation model architecture for AC experiment.

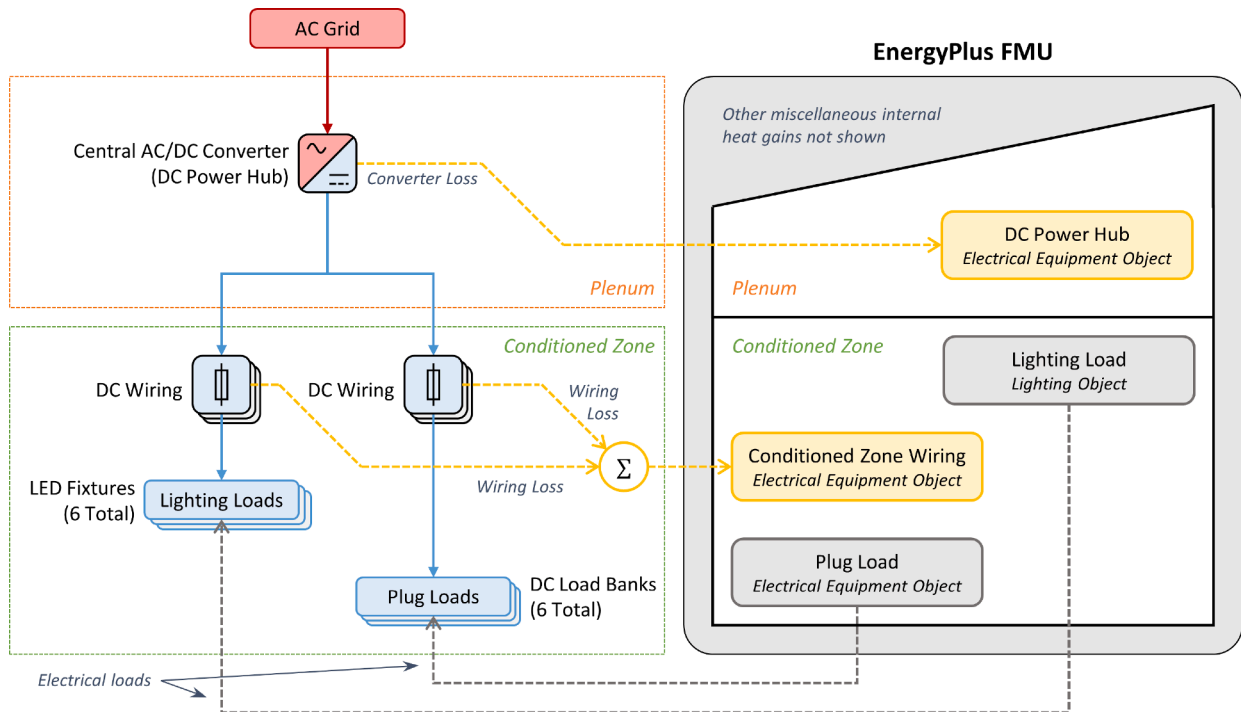


Fig. 8. Co-simulation model architecture for DC experiment.

of adjacent cell 3A was set to the measured values during the experiments to capture heat transfer between the cells.

Each test cell has a dedicated AHU with economizer, hot water coil, chilled water coil, and supply fan. Because detailed AHU design information and performance curves were not available, we instead modeled the AHU as a packaged terminal air conditioner, which serves the zone directly and includes a direct expansion cooling coil, a natural gas heating coil, and a constant volume supply air fan (Fig. 10). We established the validation boundary at the output side of the AHU (delivered air-side

heating and cooling energy). Therefore, the substitution of a packaged unit in the model does not affect the validation study.

The electrical systems in the whole-building model are represented using Lights and ElectricEquipment EnergyPlus objects. The model uses Schedule:File objects associated with time series input data from comma-separated values files to represent the absolute load powers (W) of the light emitting diode (LED) light fixtures, programmable load banks, circulation fans, and other miscellaneous loads. Wiring losses and the power conversion losses of the integrated AC-input LED

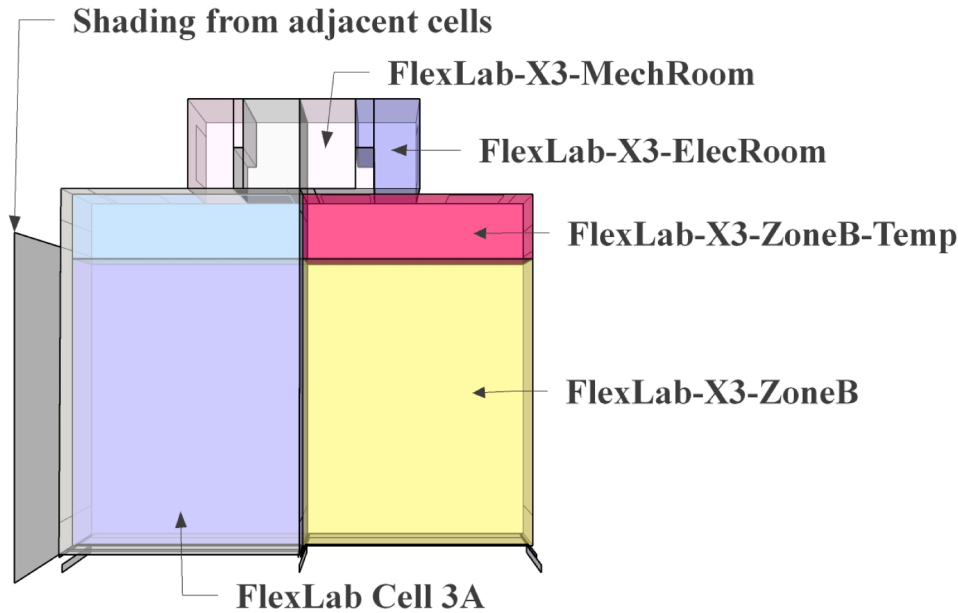


Fig. 9. Whole-building model geometry showing overhead view of thermal zones.

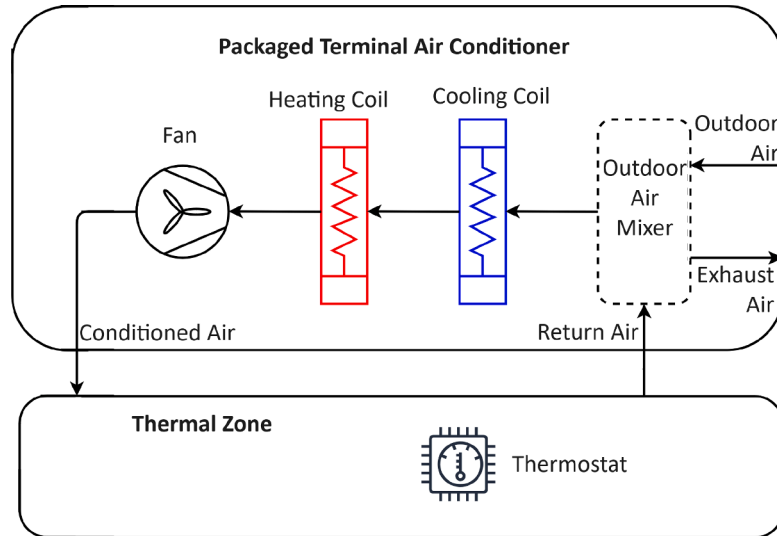


Fig. 10. Mechanical system schematic diagram.

drivers, AC/DC computer power supplies, and central AC/DC converter are modeled in BEEAM, summed by zone, and input to EnergyPlus via `ExternalInterface` objects that override the internal schedules for these loads. To ensure correct scaling, all electrical system objects have a nominal magnitude of 1 W, which are multiplied by the absolute load from the `Schedule:File` objects. Table 3 summarizes the electric system objects in the whole-building model. A single EnergyPlus model represents all four experiments; any objects not applicable to a given experiment have their power levels set to zero in the corresponding simulation.

Fig. 11 presents the time series data used for the load schedules. For the calibration experiments, all load schedules represent measured data, and the programmable load power is replaced with the measured AC input power of the programmable loads and the AC/DC computer power supplies combined. This ensures the model reflects the correct value for total internal heat gains during calibration. For the AC and DC validation experiments, the fan and miscellaneous load schedules contain measured data, and the programmable load schedule equals

the sum of the load power programmed for the six programmable DC load banks (see Section 2.1). The lighting load schedule for the AC experiment is derived from measured data using the characterized LED driver efficiency (see Section 2.2.2), while the lighting load schedule in the DC experiment is set to a constant value based on spot measurements of the DC-input LED fixture consumption during the DC experiment.

2.2.2. Electrical distribution model

The electrical distribution system model is implemented using the BEEAM Modelica library, which was developed by contributing authors and others [12]. Frank et al. [12] provide a full description of the BEEAM library, and Frank et al. [9] describe co-simulation of BEEAM with EnergyPlus.

We implemented electrical distribution system models for the AC and DC experiments only as calibration did not require co-simulation with BEEAM. We developed two electrical models: one for the AC experiment and one for the DC experiment. Of the devices represented in Table 3,

Table 3
Electric load objects in the whole-building model.

Load	Object type	Thermal zone	Input method
LED lights	Lights	Conditioned zone	Schedule
Programmable load banks	ElectricEquipment	Conditioned zone	Schedule
Circulation fans	ElectricEquipment	Conditioned zone	Schedule
Circulation fans	ElectricEquipment	Plenum	Schedule
Miscellaneous loads	ElectricEquipment	Conditioned zone	Schedule
LED drivers	Lights	Plenum	External interface
AC/DC power supplies	ElectricEquipment	Conditioned zone	External interface ^a
Central AC/DC converter	ElectricEquipment	Plenum	External interface
LED fixture wiring (AC)	Lights	Plenum	External interface ^b
LED fixture wiring (DC)	ElectricEquipment	Conditioned zone	External interface ^a
Load bank wiring	ElectricEquipment	Conditioned zone	External interface ^a

^a All conditioned zone losses (from wiring and/or power supplies) are combined in a single ElectricEquipment object

^b In the AC model, LED fixture wiring losses are included with the LED driver loss object

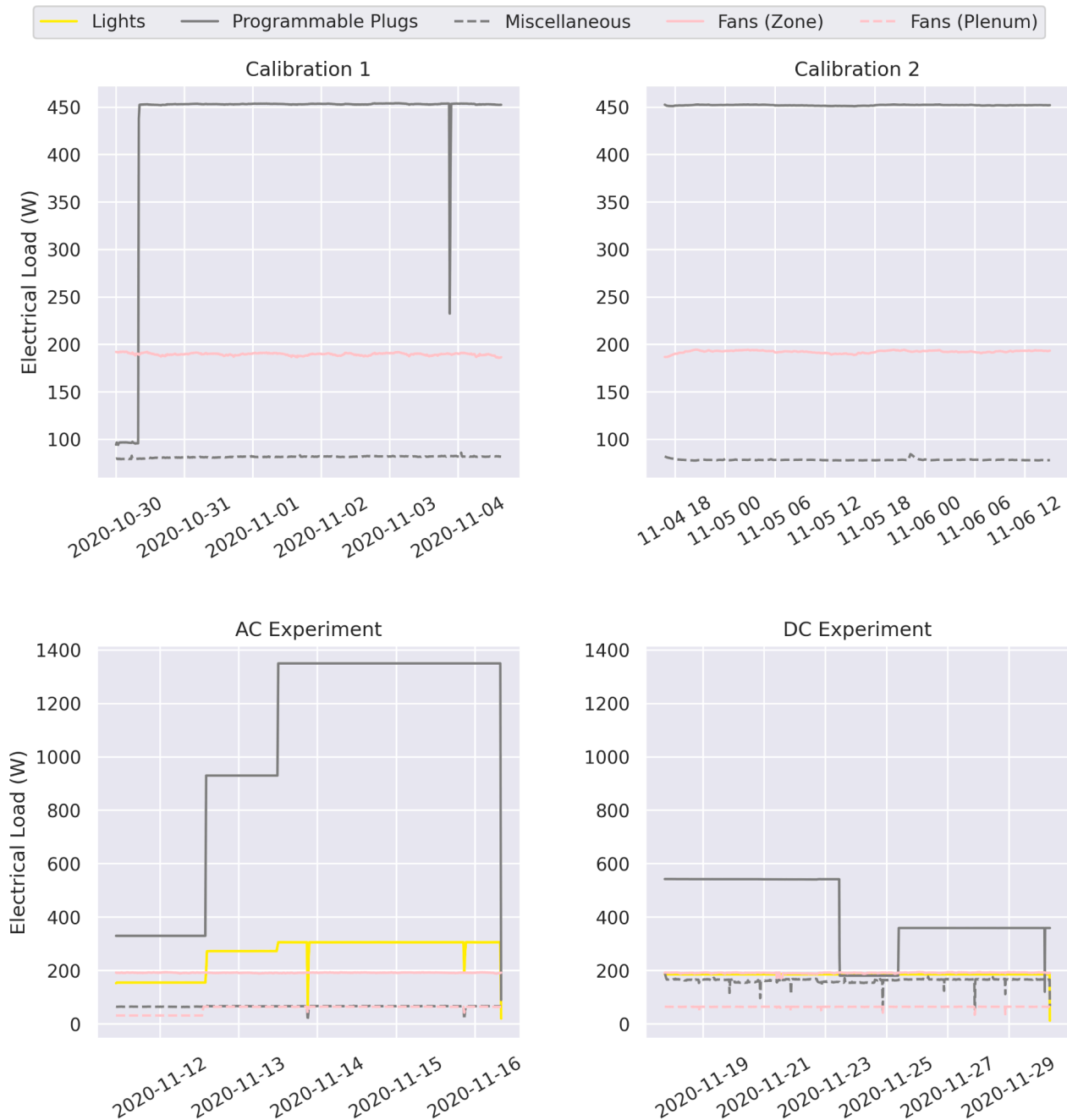


Fig. 11. Measured electrical loads during experiments.

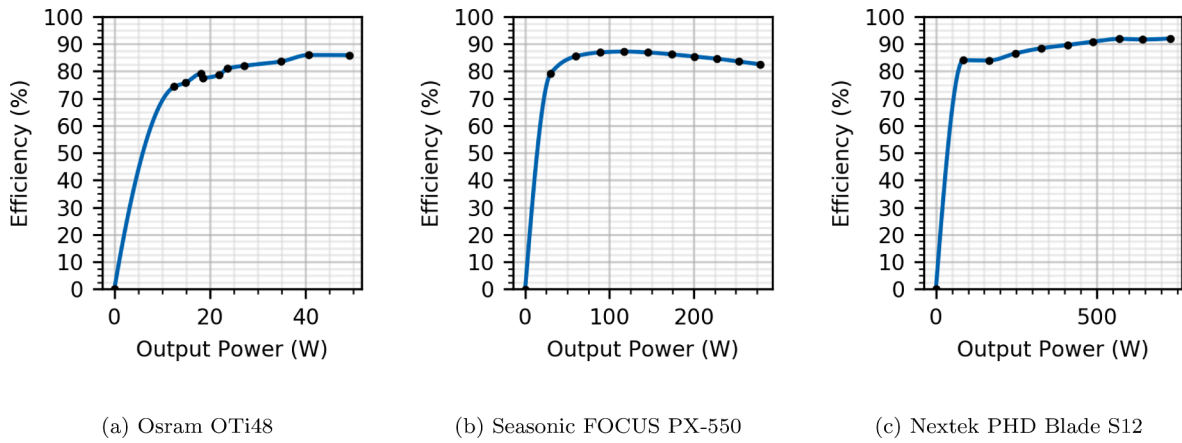


Fig. 12. Efficiency curves for power electronic converters.

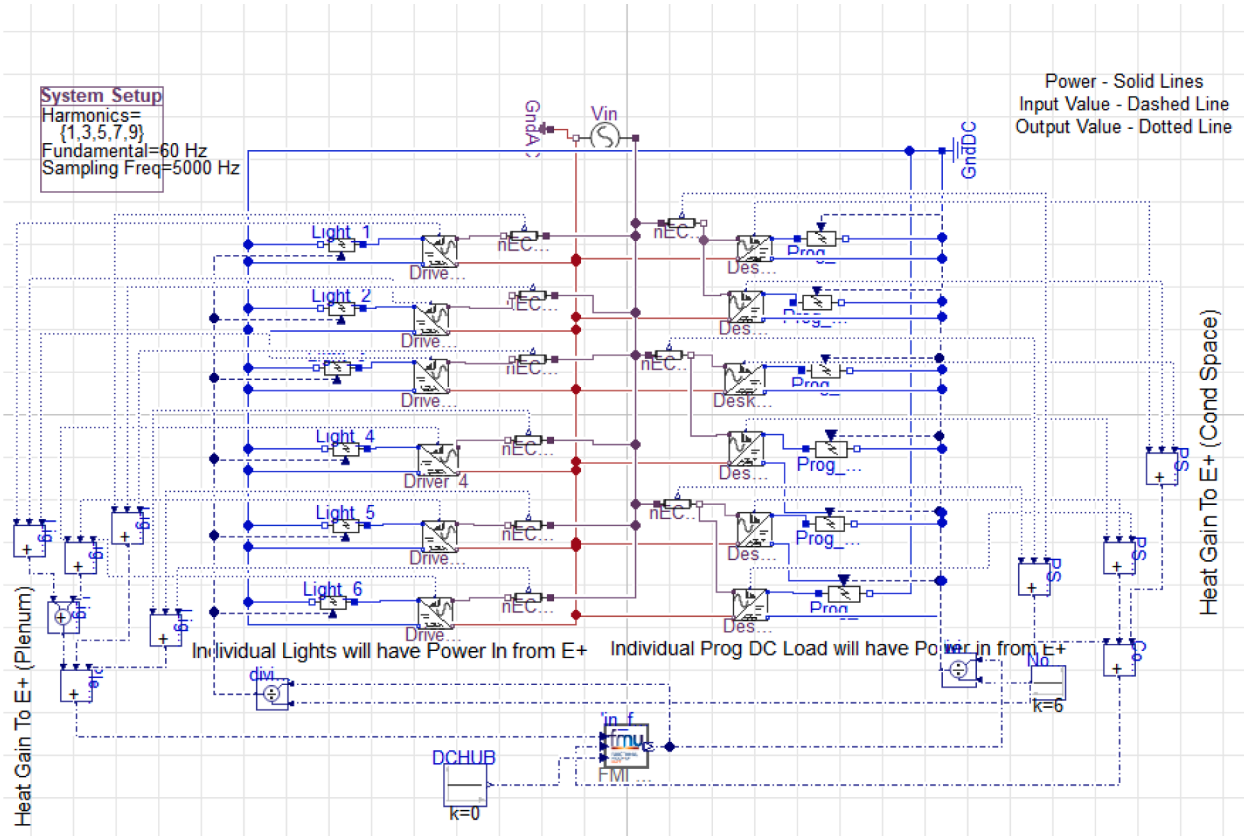


Fig. 13. Modelica model for the AC experiment.

only the power electronic converters and their associated DC loads are modeled in BEEAM (see Figs. 7 and 8). We omitted the circulation fans and miscellaneous loads from the electrical model because they are continuously operating, have near-constant power draw, and do not affect the modeled power electronic converter losses.

For the AC experiment, we modeled the cable losses for cables serving the LED drivers (in the plenum) and the AC/DC power supplies (in the conditioned zone). For the DC experiment, we modeled cables from the central AC/DC hub to the LED lights and to the programmable DC load banks (both in the conditioned zone). The electrical losses related to permanent wiring in the building, circulation fan, and miscellaneous load were not included in either model as they were estimated to be negligible.

The efficiency curves and harmonic data for the integrated AC LED light driver (Osram OTi48), AC/DC power supply (Seasonic FOCUS PX-

550), and central AC/DC converter (Nextek PHD Blade) came from independent device characterization done in a laboratory. We measured the input and output power and waveforms of each device with a resistive DC load at 11 load steps spanning 0%–100% of the device's power rating. We then used the power measurements to compute the efficiency curves for each converter (Fig. 12) and used the waveforms to generate the harmonic spectra needed for the converter models [11].

For both experiments, the EnergyPlus model was embedded within the BEEAM electrical models as an FMU, as described in Section 2.2. The schedules in EnergyPlus modulate the operating points of the lighting and programmable DC loads in BEEAM. EnergyPlus outputs the total DC lighting load and total DC programmable load as two values. Because all individual loads of each type have an identical operating pattern, the electrical model divides the FMU power output values by six to obtain individual load powers.

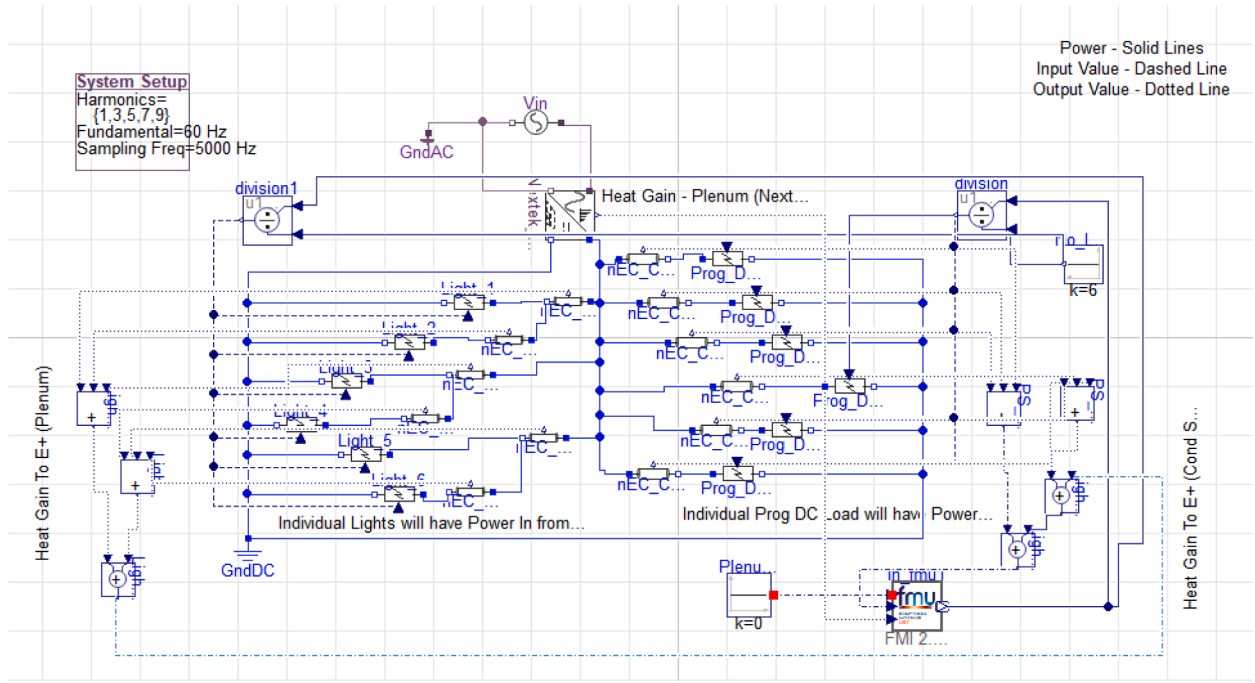


Fig. 14. Modelica model for the DC experiment.

The AC experiment model (Fig. 13) consists of six LED lights individually connected to six AC-input drivers, and six programmable DC loads each independently powered through an AC/DC power supply. The drivers and power supplies are connected to a single-phase 120 V_{AC}, 60 Hz source, matching the nominal source voltage and frequency used in the AC experiment. The calculated power of the lights and programmable DC load power were outputs from the EnergyPlus FMU to the BEEAM model, as described above. The BEEAM model calculates and separately sums the total electrical losses for the plenum and conditioned zone and returns them as input values to the EnergyPlus FMU.

The AC LED lighting fixtures (GO-LED-24-46-35-UNV) had integrated drivers (Osram OTi48) inside each fixture; we did not have access to the electrical measurement point between the driver and the LED array. During the experiment, we could measure only the combined power consumed by the LED array and driver, meaning the sum of the output power and the driver losses. Therefore, we derived the DC LED lighting power schedule for the AC-input lighting fixtures from the driver efficiency characterization data (Fig. 12a). We note that an independent measurement of the DC output power of the LED drivers would have been a more accurate method for generating the lighting power schedule.

The DC experiment model (Fig. 14) consists of a centralized AC/DC converter powering the six DC-input driverless LED lights and six programmable DC loads. Because the central converter can maintain a constant current on its channels, separate drivers for the LED lights were not required in the DC experiment. The central converter is connected to a single-phase 120 V_{AC}, 60 Hz source, matching the source used in the DC experiment. The central converter electrical losses are provided as input values to the EnergyPlus FMU for the plenum heat gain, and the conditioned zone wiring losses are provided as conditioned zone heat gain.

2.3. Validation methodology

Given known end-use loads, the co-simulation model should accurately predict the combined electrical, mechanical, and thermal performance of the building. To validate this outcome, we compared measured

and modeled values of four model outputs for both the AC and DC experiments:

1. Electrical distribution system input power (W)
2. AHU-delivered cooling (W)
3. Conditioned zone temperature (°C)
4. Plenum temperature (°C).

The electrical distribution system input power represents the combined loads and losses of the devices modeled in BEEAM (lights and programmable loads, with their associated wiring and converters), while the AHU-delivered cooling represents the air-side measurement of cooling to the conditioned zone (excluding fan energy).

During the calibration phase of the study, we adjusted the parameters of the whole-building energy model to produce a correct response for the zone temperature, plenum temperature, and AHU-delivered cooling for the measured loads present in the experiment. The BEEAM model did not require calibration; it used independent characterization data for each of the AC/DC converter models present in the experiments (see Section 2.2.2). During the validation phase, we assembled the calibrated EnergyPlus and BEEAM models into a pair of co-simulation models (one each for the AC and DC experiments; see Section 2.2), applied the end-use load schedules for the AC and DC experiments, and exported the model outputs for comparison with the experimental data. During the validation simulations, all whole-building energy model parameters were held constant at their calibrated values.

3. Results

To quantify the accuracy of the models, we computed normalized mean bias error (NMBE) and the coefficient of variation of root-mean-square error (CV(RMSE)) for the quantities of interest using the standard formulas defined in ASHRAE Guideline 14 [33],

$$NMBE = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{(n - p) \times \bar{y}}, \quad (1)$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{(n - p)}}}{\bar{y}}, \quad (2)$$

in which n is the number of observations, y_i represents the measured observations, $\hat{y}_i$ represents the modeled observations, $\bar{y}$ is the arithmetic mean of the measured data, and $p = 1$ for calibrated simulations. (Here, we reference ASHRAE Guideline 14 for the NMBE and CV(RMSE) formulas. However, we note that Guideline 14 is more typically applied to hourly whole-building energy data in the context of calibrating whole-building energy models, not for validating subsystem models as is done here.)

3.1. Whole-building model calibration

The approach for whole-building model calibration involved two steps: an architectural calibration based on a free oscillation period (1st calibration experiment) and a mechanical system calibration with conditioned operation (2nd calibration experiment). Both calibrations used the Parametric Analysis Tool [34] 3.1.0 to perform sensitivity analyses, down-select the parameter space, and then to optimize the calibrations using Latin Hypercube Sampling [35]. First, we adjusted the building's architectural parameters to calibrate the zone and plenum temperatures during the free oscillation period to their measured values. Second, with the architectural parameters fixed, we adjusted the mechanical system parameters to calibrate the AHU-delivered cooling to the values observed in the 2nd calibration experiment. Table 4 summarizes the model calibration results.

Table 4

Whole-building model calibration results.

Modeled quantity	NMBE	CV(RMSE)
Average conditioned zone temperature	-0.0 %	1.3 %
Average plenum temperature	0.1 %	0.8 %
AHU cooling delivered	-0.5 %	6.5 %

3.1.1. Architectural calibration

The model initially exhibited a poor match between measured and modeled conditioned zone and plenum temperatures (Figs. 15 and 16). Specifically, there were three issues with the initial simulated temperature profiles:

1. There was a significant mismatch in the starting temperatures, indicating incorrect initial conditions achieved during model warm-up.
2. The predicted zone temperature did not show the diurnal variation observed in the measured data, suggesting that the overall thermal transmittance (U-factor) of the envelope was too low.
3. The modeled temperature increase over time was greater (conditioned zone) or less (plenum) than in the experiment, indicating an imbalance in the modeled internal heat gains.

These observations were used to inform the initial sensitivity analysis during the calibration by identifying architectural parameters that had the greatest affect on calibration. These included (1) initializing

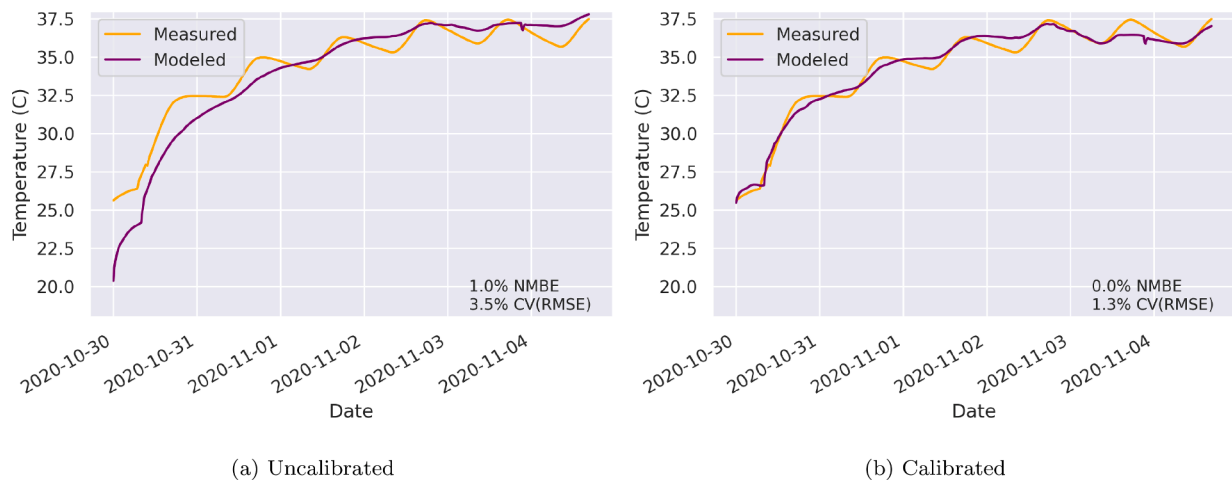


Fig. 15. Modeled free-oscillation conditioned zone average temperature pre- and post-calibration.

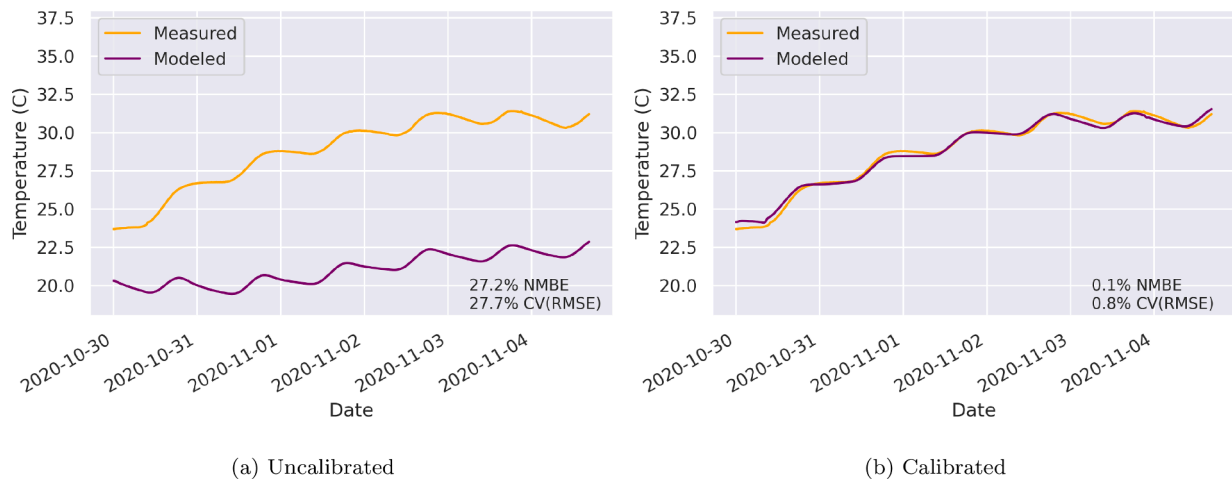


Fig. 16. Modeled free-oscillation plenum average temperature pre- and post-calibration.

Table 5
Cell 3B architectural properties.

System	U-factor range (W/m ² ·K)
Roofs	0.262 - 0.095
Walls	0.550 - 0.072
Windows	2.045 - 0.789

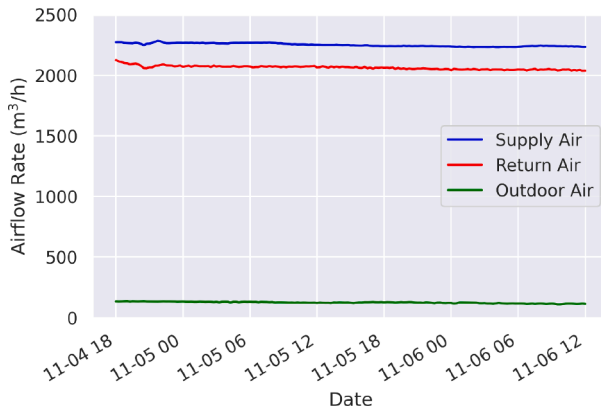


Fig. 17. Measured airflow for mechanical systems calibration.

the conditioned zone to 25.5°C for the 48 h preceding the calibration using EnergyPlus's ideal air loads feature, as recommended by Goldwasser et al. [36], (2) derating the U-factor of the south window from 1.14 W/m²·K to 2.05 W/m²·K, and (3) adding 0.04 m³/s (85.5 ft³/min) of air flow between the zone and plenum to approximate convective heat transfer from the higher temperature zone to the lower temperature plenum through leakage in the ceiling tiles. The change in the south window performance reflects uncertainty in the effective insulation of the covered window assembly. Table 5 summarizes the architectural properties of the whole-building model.

3.1.2. Mechanical system calibration

Calibration of the mechanical system focused on the AHU's thermal load (delivered cooling and heating). During the 2nd calibration experiment, the AHU operated solely in cooling mode with the south window U-factor fixed at the calibrated value. The 48 h initialization warm-up was left on, but did not affect the mechanical calibration due to the significant temporal separation. The air mixing between the conditioned

zone and plenum was reduced to zero while the AHU was operating based on the assumption that air flow was dominated by mechanical rather than natural convection.

Initial calibration results showed poor matches between measured and modeled cooling in both magnitude and profile (Fig. 18). The experimental data showed significant tracking of the cooling load against the outdoor conditions, indicating a ventilation load on the mechanical system. Airflow measurements obtained from the 2nd calibration experiment showed an imbalance of approximately 190 m³/h (8%) between the AHU supply and return airflow rates, and an outside airflow rate of approximately 120 m³/h measured at the AHU (Fig. 17), suggesting that outside air was being introduced via the mechanical system (i.e., from controls-induced minimum ventilation, or duct or damper leakage) rather than by infiltration. We modified the design supply air temperature to 18.86°C, which was the minimum measured value observed during the experiment, as a known value prior to sensitivity analysis and calibration.

Calibration of the mechanical system focused on several unknown fan parameters (motor efficiency, total efficiency, and total static pressure [TSP]), which add heat to the air stream being cooled, and the outdoor air flow rate, which the measured data showed varied slightly during the calibration period. Initial sensitivity analysis showed that TSP and outdoor air flow rate affected the calibration results more than the fan efficiencies. Therefore, the fan motor efficiency and total efficiency were fixed at default values for the sampling simulations. Latin Hypercube Sampling significantly improved the calibration at a TSP of 2690.8 Pa and an outdoor air flow rate of 122.5 m³/h showing a cooling load NMBE of -0.5% and a CV(RMSE) of 6.5% (Fig. 18).

3.2. Validation

For model validation, we embedded the calibrated whole-building energy model FMU within the AC and DC electrical distribution system Modelica models, as described in Section 2.2. We then co-simulated the models using the observed weather conditions and scheduled internal loads as inputs to the whole-building model while holding all other parameters constant at their calibrated values. To evaluate the impact of electrical distribution losses on modeled building performance, we also simulated the same whole-building energy model without using co-simulation, using the same weather conditions and scheduled loads. In the standalone (EnergyPlus only) whole-building model, heat gains from the wiring and converter losses were fixed to zero. (This would be standard modeling practice in the absence of specific loss characterization data.) We compared both sets of model outputs to the measured data quantitatively, by calculating NMBE and CV(RMSE), and qualitatively, by analyzing the model time series data.

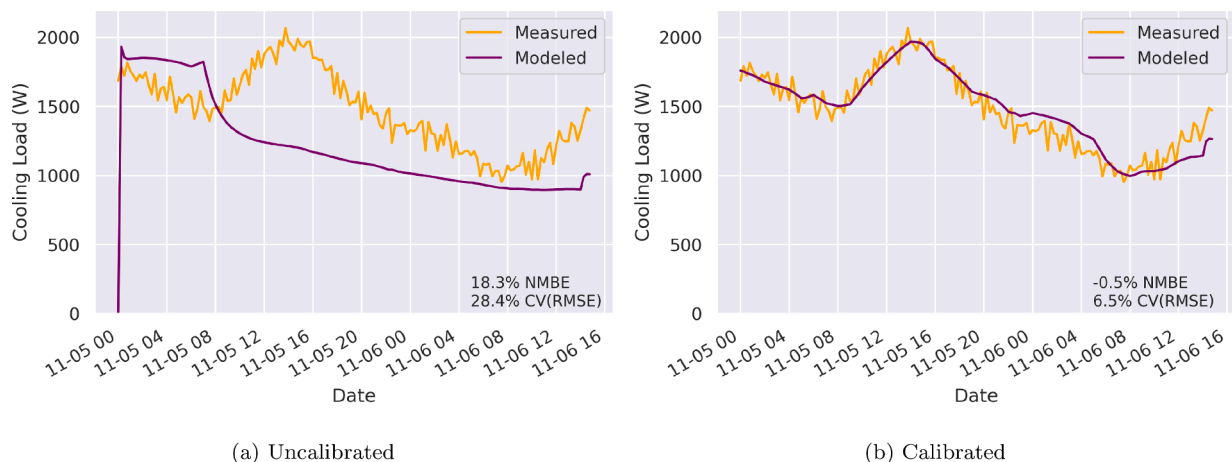


Fig. 18. Modeled cooling load pre- and post-calibration.

3.2.1. AC Distribution

Table 6 provides the values of the co-simulation model validation metrics for the AC experiment, and Fig. 19 displays time series plots of the modeled and measured data for electrical input power, delivered cooling, and zone temperatures. The co-simulation model very accurately predicted the total electrical input power, slightly underpredicted the temperatures of the plenum and conditioned zone, and slightly overpredicted the delivered cooling. The dynamics of the model generally matched the dynamics observed in the measured data. The EnergyPlus only model significantly underpredicted the total electrical input power, slightly underpredicted the total cooling load, and predicted the plenum temperature somewhat better than the co-simulation model.

3.2.2. DC Distribution

Table 7 provides the validation metrics for the DC experiment, and Fig. 20 displays the associated time series plots. For the DC experiment, the co-simulation model slightly underpredicted the electrical input power and zone temperatures and significantly underpredicted the

Table 6

AC Experiment validation results.

Modeled quantity	Model type	NMBE	CV(RMSE)
Electrical input power	Co-Simulation	0.4 %	2.2 %
	EnergyPlus	-14.2 %	14.4 %
AHU cooling delivered	Co-Simulation	2.1 %	7.9 %
	EnergyPlus	-5.7 %	8.6 %
Average conditioned zone temperature	Co-Simulation	-1.6 %	1.7 %
	EnergyPlus	-1.6 %	1.7 %
Average plenum temperature	Co-Simulation	-15.2 %	15.3 %
	EnergyPlus	-12.2 %	12.2 %

delivered cooling. In comparison, the EnergyPlus only model underpredicted all measurements other than zone temperature by greater magnitudes than the co-simulation model. The dynamics of the models again generally matched the dynamics observed in the measured data.

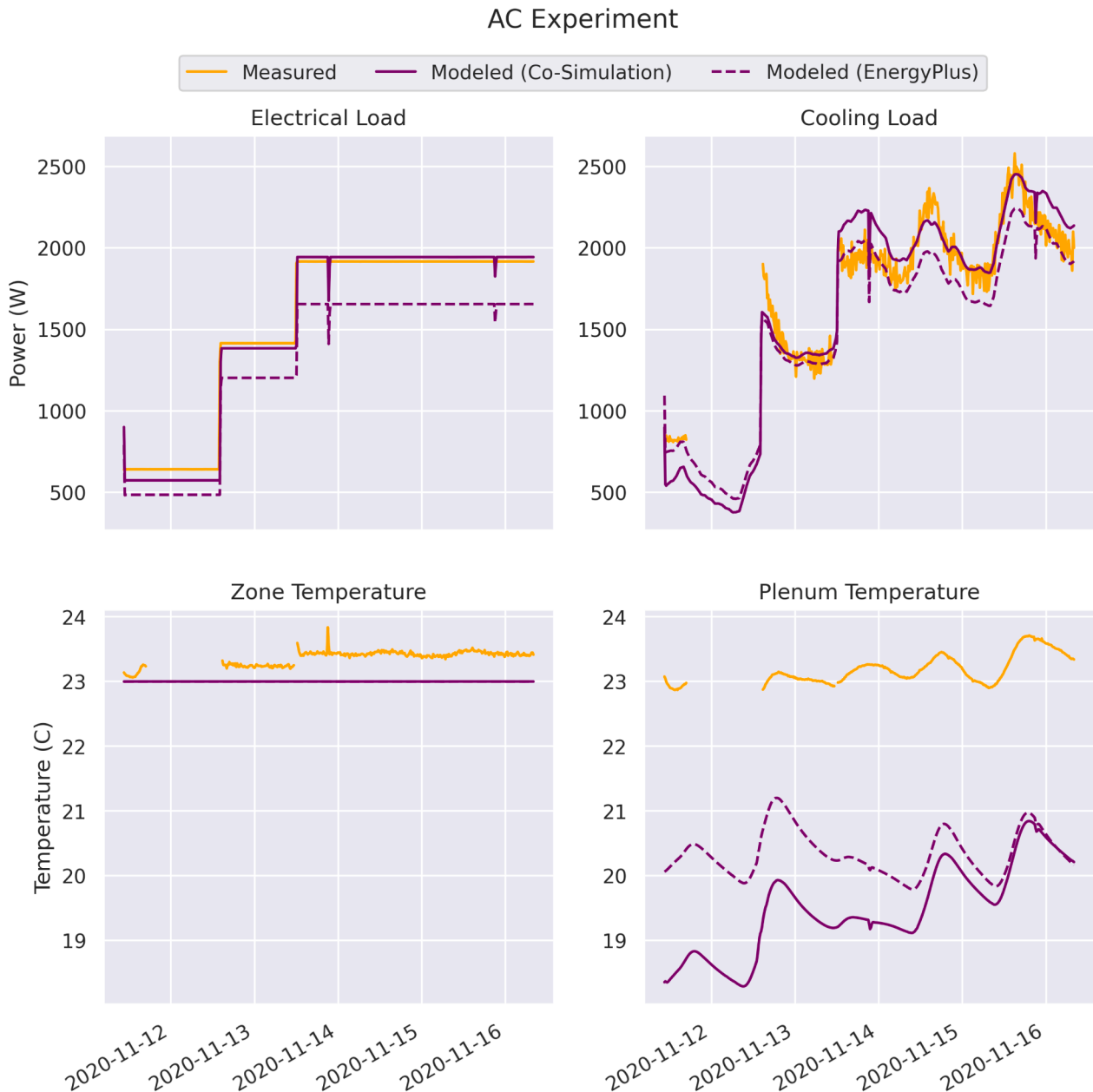


Fig. 19. AC experiment validation results.

The large gap in the measured data reflects a two-day period during which the HVAC system was inadvertently disabled, resulting in zero delivered cooling and large swings in the zone temperatures. We removed the measured values during this time period from the plotted validation data as described in Section 2.1 (see Table 1), because otherwise they would distract from the valid data. Likewise, the NMBE and CV(RMSE) values for the temperatures and delivered cooling are calculated excluding the HVAC outage. The model outputs, however, span the outage and provide a prediction of how the FLEXLAB cell might have behaved in the absence of the outage.

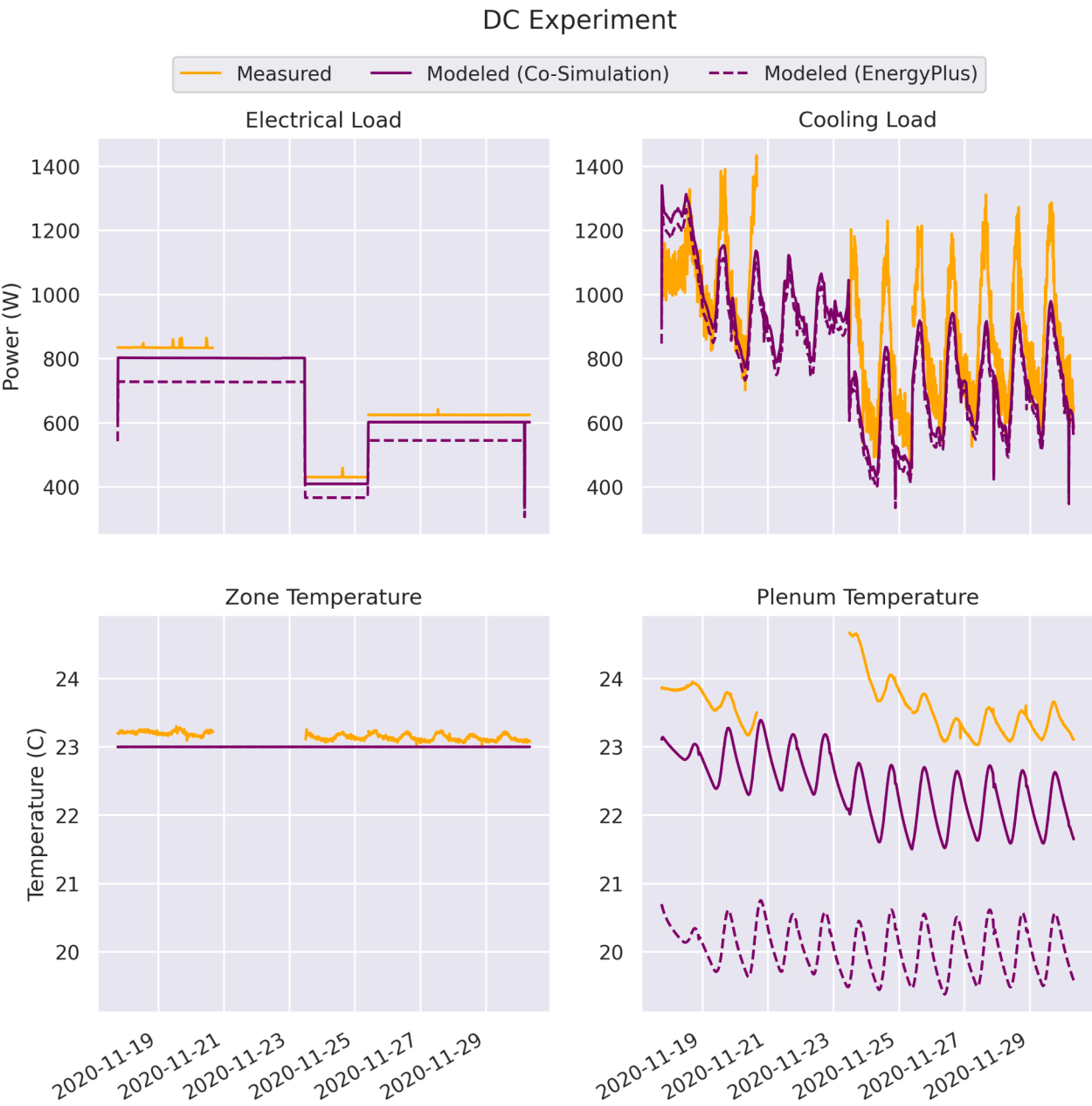
4. Discussion

The co-simulation models were stable during simulation and the validation results demonstrate good agreement between the models and the experimental data. The results establish strong experimental evidence

Table 7
DC Experiment validation results.

Modeled quantity	Model type	NMBE	CV(RMSE)
Electrical input power	Co-Simulation	-4.0 %	4.4 %
	EnergyPlus	-13.1 %	13.5 %
AHU cooling delivered	Co-Simulation	-11.1 %	18.2 %
	EnergyPlus	-15.0 %	20.5 %
Average conditioned zone temperature	Co-Simulation	-0.7 %	0.7 %
	EnergyPlus	-0.7 %	0.7 %
Average plenum temperature	Co-Simulation	-5.2 %	5.5 %
	EnergyPlus	-15.0 %	15.1 %

for the accuracy of the co-simulation approach and illustrate the benefits of including electrical distribution system loss modeling compared to using a whole building energy model alone.



4.1. Model accuracy

Overall, the co-simulation models had excellent accuracy with respect to the electrical distribution system power flows and reasonable accuracy with respect to the test cell's thermal and mechanical system behavior. During the experiments, the outside air temperature averaged approximately 12°C and never rose above 19°C, such that the test cell experienced significant heat loss through the envelope, and a significant fraction of the AHU's overall cooling was attributable to intake of outside air. These heat losses largely offset solar heat gains, such that internal gains became the primary driver of the delivered cooling. This result leads to two key observations. First, any errors in the calibrated insulation value of the envelope would have contributed a nearly proportional percentage error to the modeled cooling load of the AHU; this may have contributed to the error in predicted cooling in the DC experiment. Second, errors in the modeled electric input power also directly translate to proportional errors in the modeled cooling, demonstrating the importance of accurate models for internal heat gains attributable to electric loads.

The modeled losses associated with AC/DC power conversion ranged from 88 W to 284 W for the AC experiment and from 35 W to 62 W for the DC experiment, representing, on average, 14.5 % and 8.4 % of the total electrical input power in the AC and DC experiments, respectively. Because these power conversion losses become heat gains within the conditioned zone and plenum, they directly affect the modeled cooling. Therefore, if the whole-building model's thermal properties were perfectly calibrated, an underprediction of power conversion losses would yield an underprediction of similar magnitude for the required cooling. This effect is clear in the EnergyPlus only model output, where both total electrical load and cooling load are underpredicted compared to the co-simulation model.

The accuracy of the electrical distribution model was better for the AC experiment than for the DC experiment. In past studies, we have observed that BEEAM more accurately predicts the losses of single-input, single-output power electronics converters (such as load-packaged AC/DC converters) than it predicts the losses of multichannel power hubs (such as the Nextek PHD Blade). We hypothesize that the accuracy of an efficiency curve modeled solely as a function of output power is inadequate for multichannel devices, in which the distribution of power among the channels may affect the operating efficiency. This is a recommended area for future research. Other potential sources of error include small variations in efficiency between converters and changes in efficiency attributable to voltage (which BEEAM does not currently model).

Wiring losses in building electrical distribution systems are usually negligible compared to other losses. However, resistive (I^2R) losses in low-voltage (24 V_{DC}) DC wiring are proportionally higher than those in 120 V_{AC} AC wiring at the same power levels due to the higher current flowing for equivalent power transfer. We observed that modeling the low voltage cable losses for the temporary wiring for the DC experiment increased the electrical model simulation accuracy.

Potential sources of error for the temperatures and delivered cooling include incorrect assumptions regarding the adiabatic surfaces, inaccuracies in the calibrated architectural and mechanical properties, differences in the controlled zone temperature (possibly due to non-ideal thermostat placement in the experiment), differences in initialization convergence in the EnergyPlus model, and experimental measurement error. Several walls in cell 3B were modeled as adiabatic due to high insulation levels and unknown conditions in the adjacent spaces. These included the temporary north walls, which reduced the size of the conditioned zone, and the west walls separating the plenum of cell 3A from cell 3B (the walls separating the conditioned zones in cell 3A and 3B were modeled as heat transfer surfaces). Finally, any errors in measured outside air temperature or AHU airflow rates could have also contributed to error during the calibration process, producing errors in the model's calibrated properties.

Despite sources of uncertainty in the whole building model, the validation results demonstrate the benefits of using co-simulation to include detailed electrical distribution system performance. The co-simulation model predicted electric energy consumption and cooling load better than the EnergyPlus model only. The plenum temperature difference in the DC experiment shows how the location of heat gains influences predicted temperatures: including of the converter losses within the plenum improved the plenum temperature prediction by approximately 2°C.

4.2. Lessons learned

During the validation study, we identified several areas for potential improvement:

- *Measure and minimize extraneous electrical loads:* Failure to account for all electrical loads that contribute heat gains to the experiment will yield errors in the predicted internal gains of the building. All electrical loads must be accurately measured and their heat gains represented in the whole-building model. Miscellaneous loads that are not modeled in the electrical distribution system should be minimized so that the dominant sources of heat gains are those represented by the electrical model.
- *Plan ahead for intermediate electrical power measurements:* For detailed validation studies, in situ measurement of the power between converters and loads is desirable, especially if the exact value of the load power will otherwise be unknown. Unfortunately, many power electronics devices are packaged with loads in a way that precludes access for measurement of the power converter outputs. (The LED lights with integrated drivers used in the AC experiment are an example; see Section 2.2.2.) For future studies, we recommend selecting products that can be modified to measure DC power output post-converter and procuring measurement equipment capable of accurately measuring these intermediate powers.
- *Confirm HVAC systems operate as intended:* We disabled the HVAC economizing function during the experiments and therefore initially assumed the AHU would not provide any outside air to the zone. However, in practice the AHU delivered a large amount of outside air, leading to errors in our initial versions of the whole-building model. Even after we corrected the model to include the observed outside air intake, the modeled ventilation remained a source of uncertainty that detracted from the validation study. In retrospect, we should have verified proper HVAC operation using real-time measurements prior to proceeding with the experiments.

Following these guidelines will improve the quality of future validation experiments and allow more detailed comparisons of measured and modeled data, particularly for the electrical distribution system.

4.3. Sequential simulation vs. co-simulation

Co-simulation requires coordinated, simultaneous execution of multiple simulation engines with data exchange at regular intervals. In other words, co-simulation is computationally complex. Sequential simulation offers a simpler, alternative approach in which the two (or more) models are simulated sequentially: the output of each model is used as input to the next. For example, electrical distribution system performance and losses (from BEEAM) could be used as input to a whole building energy model (in EnergyPlus) to calculate heating and cooling loads.

Sequential simulation both assumes and requires that models simulated earlier are independent of the outcomes of later models. If this is not the case, the simulation results will not be accurate. Therefore, sequential simulation is not appropriate for investigating interdependencies between models. In contrast, our proposed co-simulation approach is capable of complex studies of interdependent phenomena, such as:

- Effects of distribution system losses in data centers on cooling load, where the cooling equipment electrical load also contributes to the electrical distribution system losses.
- The influence of load diversity (modeled using a whole building energy model) on electrical distribution system harmonic spectra and power factor, which in turn impact utility bills.
- Real-time control of microgrids to satisfy building demand, ensure electrical system power quality, and maintain power flows within acceptable limits.

In this validation study, the implemented electrical distribution system model depends only on scheduled load. Therefore, if the objective were only to predict the building performance, the experiment would have been a good candidate for sequential simulation. However, the primary objective was to validate the accuracy of the co-simulation approach. Validation establishes confidence in the co-simulation architecture that facilitates its use in future research, such as the complex scenarios described above.

4.4. Future work

The validation study presented in this article represents a first step toward comprehensive validation of co-simulation models using rigorous methodology, as is currently done for single-engine BPS software such as EnergyPlus. We recommend future work to refine the validation methodology for co-simulation models and to validate such models for a wider variety of physical systems. Specifically, we recommend the following avenues of research:

1. Develop instrumentation to measure power flows throughout the electrical distribution system, enabling component-level validation of complex electrical distribution system models.
2. Develop standard validation methodology and accuracy targets for co-simulation models, enabling robust comparison of modeling approaches.
3. Implement standard experimental configurations for the FLEXLAB test cells' thermal and mechanical systems and develop well-calibrated whole-building models for each configuration; this will reduce uncertainty associated with the whole-building model's properties and focus the validation on the co-simulation architecture.
4. Add variety and complexity to the electrical distribution system, such as by adding step-down transformers, infrastructure wiring, more load types, and managed DC distribution (such as Power over Ethernet or USB-C outlets).
5. Add complexity to the HVAC system and controls (e.g., variable air volume, economizing, or separate systems for ventilation and temperature control).
6. Investigate the effects of converter location on system HVAC loads, such as by relocating converters from the conditioned zone to the plenum or to an unconditioned electrical room.
7. Expand validation to multizone buildings.

In addition to future validation work, research is needed to quantify the benefit of using detailed electrical simulation with whole building energy models to improve overall model accuracy, versus using simpler loss models that can be embedded directly within EnergyPlus. The benefit of accurate electrical load and distribution models to overall load prediction accuracy is proportional to the extent that internal heat gains are the dominant driver of building heating demand, cooling demand, and overall energy consumption. Co-simulation is expected to be more beneficial when simulating data centers or large office buildings, for example, than when simulating single-family homes. Research to quantify these effects can be done more confidently with a well-validated co-simulation architecture, and such research will also inform under what circumstances and the extent to which such an architecture is needed.

5. Conclusion

This article presents a validation study of a co-simulation architecture for modeling whole-building energy performance and detailed building electrical distribution system performance based on Modelica and the Functional Mock-up Interface standard. The validation experiment used a FLEXLAB test cell with a conditioned zone, an unconditioned plenum zone, and a ducted AHU in combination with two different electrical distribution systems: a typical AC system with load-packaged AC/DC converters, and a DC distribution system with a central DC power hub. The simulation showed good agreement with the measured data, with NMBE and CV(RMSE) validation metrics less than 10 % for electrical input power and zone temperature, and less than 20 % for delivered cooling and plenum temperature. This study represents a first step toward developing comprehensive, standard validation methods for BPS co-simulation as has already been achieved for single-engine BPS software. As co-simulation capabilities for building mechanical, electrical, and thermal systems expand and mature, we recommend future work to focus and improve the models, extend validation to additional components and system configurations, and develop validation targets and standards for co-simulation models.

CRedit authorship contribution statement

Stephen M. Frank: Writing - review & editing, Writing - original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization; **Omkar Ghatpande:** Writing - review & editing, Writing - original draft, Visualization, Software, Methodology, Investigation, Formal analysis; **Jordan Shackelford:** Writing - original draft, Resources, Methodology, Investigation, Data curation; **Matthew Steen:** Writing - original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation; **Brian L. Ball:** Visualization, Validation, Software, Resources, Data curation; **Daniel L. Gerber:** Writing - original draft, Validation, Investigation, Data curation; **Arthur Santos:** Investigation, Data curation; **Richard E. Brown:** Writing - review & editing, Supervision, Resources, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

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

Acknowledgments

This work was authored in part by the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308, and by Lawrence Berkeley National Laboratory, operated for the DOE under Contract No. DE-AC02-05CH11231. Funding provided by DOE Office of Energy Efficiency and Renewable Energy Building Technologies Office Emerging Technologies Program. FLEXLAB at Lawrence Berkeley National Laboratory's component of this work was also supported by the DOE Office of Energy Efficiency and Renewable Energy Building Technologies Office under Contract No. DE-AC02-05CH11231. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Supplementary material

Supplementary material associated with this article can be found in the online version at [10.1016/j.enbuild.2025.115917](https://doi.org/10.1016/j.enbuild.2025.115917).

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