BEOP: A Framework Enabling Validation of Real-World Energy Management Systems

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***Abstract*—With the rise of renewable energy, electric vehicles, and batteries, residential buildings are evolving into prosumers, requiring energy management systems (EMSs) to optimize self-consumption and grid support. Simulations often fail to capture real-world complexities such as fluctuating weather, hardware behavior, and communication delays. To address this, we present the Building Energy Operation Platform (BEOP), a modular and scalable framework for validating real-world EMSs. BEOP supports various EMS types, integrates hardware and software components, and allows multi-resolution performance analysis. Demonstrated through a schedule-based optimization use case, we highlight the impact of real-world factors on EMS performance and advance research in forecasting, optimization, and grid stability.**

Keywords—Real-World, Energy Management Systems, Integration of Distributed Energy Resources, Grid Stability, Optimization, Forecasts.

I. Introduction

The building sector is critically relevant to tackle climate change because it accounts for over 32% of global energy demand and about 34% of energy-related CO_2 emissions, as reported in 2023 [1]. Research shows that intelligently managing energy-related assets is key to integrating environmentally friendly technologies in buildings [2]. Numerous research studies have been conducted on the simulation of building energy management, covering a wide range of control algorithms, simulation tools, and optimization strategies to enhance efficiency, flexibility, and sustainability [3].

While extensive research has been conducted on building energy management, several crucial aspects remain insufficiently addressed. Recent studies highlighted underexplored issues such as hardware non-idealities (including the efficiency drift of Battery Energy Storage Systems (BESSs) and inaccurate State of Energy estimation), delayed responses of flexible assets, phase imbalances from single-phase loads, and high solar power gradients caused by rapid weather changes. Additional challenges include communication protocol constraints, mismatches in temporal resolution between scheduling and actual system dynamics, data privacy limitations, and the lack of reactive power consideration in schedule-based controls [4].

Consequently, at the time of this paper's publication, there is also a significant lack of a comprehensive software platform that integrates these underexplored aspects. Especially since they do not align with the goals of systems streamlined for commercial and operational purposes. For example, Chamari et al. [5] propose an EMS with a service-oriented architecture emphasizing modular microservices and Application Programming Interface (API) - first design, integrating diverse communication protocols (e.g., REST, MQTT, Modbus) for Building Management System (BMS), Internet of Things (IoT), and Building Information Modeling (BIM) interoperability. However, the framework lacks dynamic system aspects like phase imbalances, sub-second transient responses, and reactive power control critical for grid stability. Others, such as the framework by Prakash et al. [6], showcase a device-diverse EMS that includes Heating, Ventilation and Air Conditioning (HVAC), refrigeration, and BESSs, featuring vendor-agnostic integration across Modbus, BACnet, and REST protocols. While implementing a grid operator control interface, an in-depth analysis of the devices' impacts on grid stability and transient behavior is lacking. Moreover, hardware non-idealities are not examined, and their framework depends on simplified models that exclude sub-second transient analysis. Modular EMS solutions such as EnergyOS [7] facilitate modular, multi-application EMS coordination to harmonize goals like cost savings and grid stability through standardized resource sharing and scheduling. However, it does not evaluate real-world dynamics or hardware non-idealities, such as phase imbalances or sub-second system responses, which are essential for comprehensive research and deployment. In summary, review papers like Sievers and Blank [8] or Han et al. [9] show that while energy management systems are widely recognized for their role in integrating and optimizing multi-energy assets such as Photovoltaik (PV), heat pumps, and electric vehicles (EVs), including their grid interface and potential for grid stability, current research often lacks evaluation of system dynamics and hardware non-idealities, limiting insights into high-frequency and unconventional operational behaviors.

The remainder of the paper is structured as follows: Section II presents BEOP and its innovative capabilities. Section III presents an exemplary optimization problem used to validate the proposed framework. Section IV discusses the results, and Section V concludes this work.

II. Building Energy Operation Platform (BEOP)

The Building Energy Operation Platform (BEOP), illustrated in Fig. 1, is a modular and scalable framework for validating real-world EMSs and EMS algorithms, incorporating flexible components such as BESSs. It supports both rule-based EMSs, which operate under predefined conditions, and schedule-based EMSs, which rely on forecasts and optimization to manage control variables for future operations. BEOP enables multi-resolution analysis (e.g., hourly, 15-minute, seconds, or sub-seconds), allowing detailed evaluation of energy and power management, communication delays, and hardware response times. The framework integrates diverse devices such as BESSs and other components through the device operation service and predefined adapters. Further external forecasting or optimization services can be connected through generic interfaces, supported by an asynchronous communication structure. Developed using Domain-Driven Design [10] and Clean Architecture [11] principles, BEOP remains modular and expandable. The interconnected hardware and BEOP ensure traceability by continuously recording algorithm states and measurement data, enabling researchers to validate EMS performance, address operational challenges, and refine real-world implementations.

In more depth, the architecture and the environment of BEOP can be segmented into the following categories: internal services, provided services, and hardware and data access.

A. Internal Services

The BEOP Service is the platform's central coordination component. It manages experiment execution, stores configuration data, and orchestrates and collects the data for the supporting services for device control, forecasting, and scheduling. The service exposes a REST API as the primary access point for user interaction and acts as the system's main control interface.

An experiment encapsulates all relevant configurations for an energy-related test case. This includes start and end times, the devices to be controlled, selected control or optimization strategies, forecasts, schedules, and mappings to device setpoints. Experiments can be flexibly created, modified, and reused for different research scenarios via the BEOP Service.

The Device Operation Service is responsible for the direct control of physical devices such as batteries, loads, or

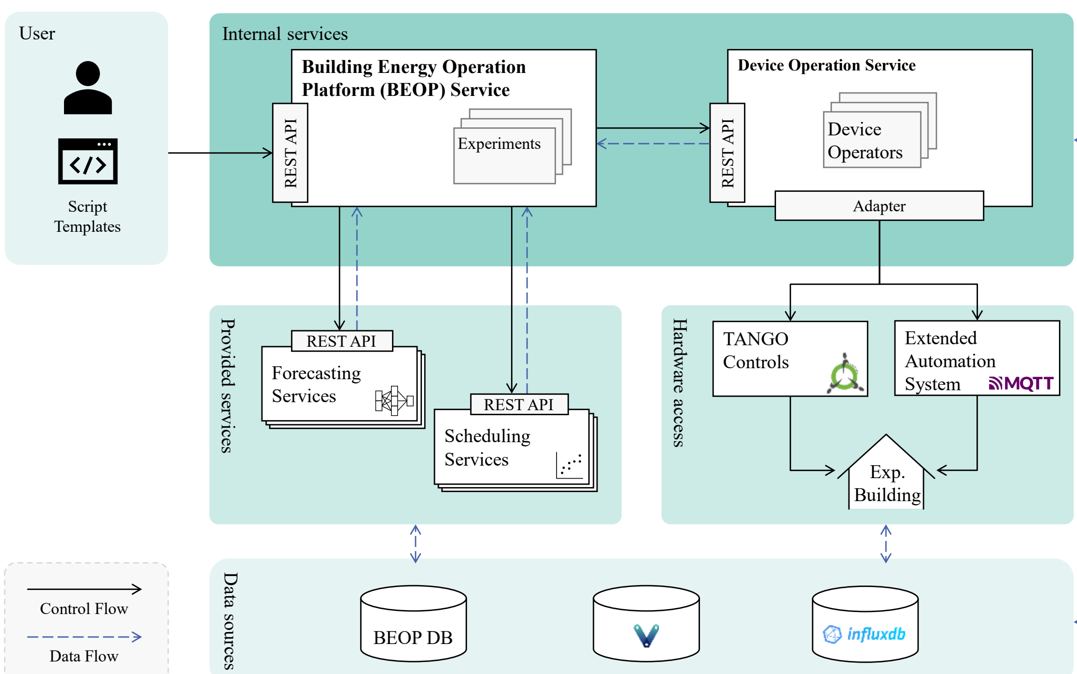

Fig. 1: The BEOP core with provided services and interfaces to the real hardware, describing control and data flows.

generators. It communicates with the hardware using adapters for TANGO (see section C) and MQTT-based systems. It manages device operators, which execute the control logic in configurable time intervals.

To address the limitations of typical real hardware, the Device Operation Service enables customizable control of the hardware. For instance, as demonstrated in Fig. 2, a PID controller is employed to control the BESS's power output via a modified setpoint (for the underlying battery control loop), thereby ensuring a stationary accuracy of the setpoint. In this instance, the process variable of the BESS is retrieved by the interface of the BESS and is sampled at a given rate of one second. Within the framework, it is possible to adapt different time granularities and process variables for each component and other measurement devices. Standard control algorithms, such as PID controllers and filters, can be integrated, and custom controllers can be incorporated.

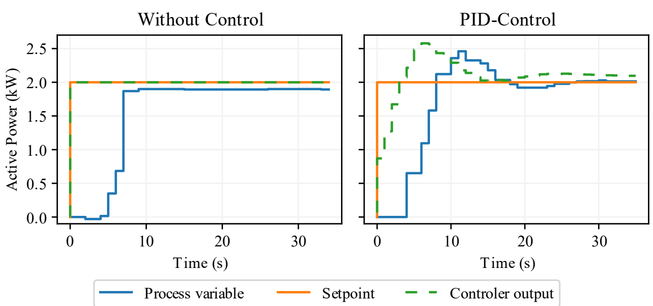

Fig. 2: Typical home BESS step response of adapting a setpoint with (right figure) and without (left figure) control of the device operation service using the BESS's response time.

B. *Provided Services*

These services provide core capabilities for generating forecasts and optimization-based control schedules. Forecasting Services predict key quantities such as energy consumption and generation, while Scheduling Services compute control strategies based on the forecasts and defined objectives. Both tasks are executed asynchronously via REST APIs, allowing for decoupled and scalable integration of computationally intensive models. The BEOP service handles task submission, status monitoring, and result retrieval. This modular design ensures flexibility and extensibility, enabling researchers to integrate custom forecasting or scheduling logic as needed.

C. *Hardware Access and Data sources*

The hardware access layer of the BEOP platform enables interaction with physical devices in the research laboratory through two main systems: TANGO Controls, an open-source SCADA framework, and the Extended Automation System, which leverages the MQTT protocol for lightweight, real-time communication. TANGO is well-suited for structured device control and monitoring, while MQTT enables high-frequency data exchange and event-driven interactions with distributed components. A unified adapter layer within the BEOP architecture abstracts both systems. This abstraction ensures a consistent interaction for higher-level services, such as the device operation service.

The BEOP platform utilizes three complementary data sources to support real-time control and experiment management. The MQTT broker enables high-frequency, real-time access to live measurement data from the experimental infrastructure. It is particularly suited for applications where up-to-date sensor values are critical, such as in control loops. The InfluxDB time-series database stores historical measurements, allowing for detailed evaluation of experiments and performance tracking over time. Finally, the BEOP database holds configuration data, logs, experiment metadata, and system states. Together, these data sources provide a robust and flexible foundation for the operation, analysis, and reproducibility of experiments within the BEOP platform.

D. *Summary*

The Building Energy Operation Platform (BEOP) is a modular and scalable framework specifically designed to validate real-world EMS applications. BEOP incorporates advanced functionalities comparable to the established benchmark systems, including compatibility with various forecasting methods and optimization algorithms, thereby ensuring seamless interoperability with a broad spectrum of hardware components. Furthermore, the BEOP effectively manages varying service response times by executing computationally intensive tasks asynchronously. Its generic, modular architecture ensures extensibility, building upon contemporary software and service-oriented structures like those introduced by Wölfle et al. [12].

Beyond these established functionalities, BEOP introduces novel capabilities essential for investigating EMS impacts within emerging renewable energy systems, particularly regarding grid stability and practical device behavior. This is the foundation for measuring phenomena like phase imbalances, system dynamics, and responses to limitations set by distribution system operator (DSO). Moreover, it addresses hardware non-idealities in critical components such as photovoltaic systems, heat pumps reacting to operational constraints, and electric vehicle charging behaviors, as discussed by Caro et al. [13]. BEOP also facilitates flexible management of temporal granularities, enabling adjustment of scheduling intervals for loads and generation, as Parisio et al. [14] highlighted. The platform allows researchers to configure customizable experiments and capture data at high resolution across numerous parameters, thus ensuring transparency, reproducibility, and traceability. Finally, its streamlined structure accommodates integration of additional lab-level devices, including grid simulators, BESSs, and wind turbines, while maintaining a focused, building-level perspective.

III. Case Study: Software Validation Via Dispatchable Feeder Optimization in the Energy Lab Infrastructure

This case study aims to evaluate the interaction between an EMS and its underlying EMS algorithm in a realistic setting. Rather than focusing on a single optimization strategy, the purpose of BEOP and EMS validation is to assess the combined behavior of hardware and software components as a system. By leveraging instrumentation and measurement capabilities, we can observe the real-world performance of EMS algorithms and investigate the effects of hardware non-idealities, communication overheads, discretization choices, and modeling simplifications.

For this specific case study, we use the Dispatchable Feeder (DF) Optimization [15] as the EMS algorithm. The DF was selected for several reasons: it is readily available for deployment; it represents a schedule-based optimization approach, which is a relevant class of EMS strategies characterized by a defined planning horizon; and most importantly, it is grid-supportive, meaning that it explicitly considers external grid constraints and objectives. As such, DF provides a meaningful example of how EMS algorithms can be evaluated in terms of system-level impact and practical applicability using the BEOP framework.

A. Software and Chosen Exemplary Optimization Problem

We employed an exemplary schedule-based EMS, the deterministic dispatchable feeder optimization problem [15]. The dispatchable feeder consists of two components: a BESS and a residual load combined with a PV. The dispatchable feeder optimization problem uses residential prosumption forecasts and commits to an optimized power exchange schedule to the grid one day in advance. The BESS's flexibility can then be leveraged during intraday execution to adhere to the committed schedule as closely as possible. In our use case, the dispatchable feeder tries to follow the committed schedule as long as it is physically possible. To employ a simple forecast, a persistence forecast with a deterministic scheduling algorithm [15] is applied. The persistence forecast of the prosumption uses a seven-day load offset and a two-day generation offset to attribute the weekly schedule of load and use the latest solar data available at noon.

B. Hardware and Infrastructure

The setup employed for the case study utilizes one of the experimental buildings in the Energy Lab [16, 17]. The Energy Lab is a large-scale research infrastructure at KIT developed to investigate research questions concerning different energy related topics. The equipment important for the DF problem installed in this building is listed in Table 1. It should be noted that the building is also used for office purposes. This renders the behaviors of the people in the residence a significant factor in the context of real load behavior.

As illustrated in Fig. 3, four power meters are employed to measure the power distribution, either to the experimental grid or the public low-voltage (LV) network, with a time resolution

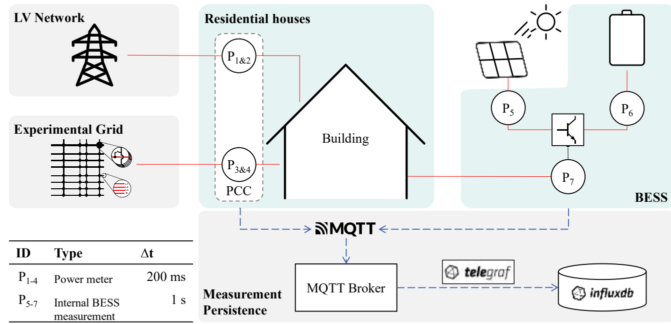

Fig. 3: Detailed experimental building setup featuring energy flows (red) and information flows (blue), showing power meters (P) monitoring the building's grid power intake of the LV network ($P_{1\&2}$) or the experimental grid ($P_{3\&4}$) and the BESS's generation and storage ($P_5 - P_7$) connected via MQTT using Telegraf and InfluxDB.

of 200 milliseconds. The hybrid inverter, which combines the functions of the BESS and the PV inverter, allows the power meter P_7 to measure only the combination of the PV and the BESS. Via the hybrid inverter's interface, which only allows measurements with a resolution of 1 s, it is possible to differentiate between PV and BESS power, but these values can only be retrieved in a 1-second resolution, and the control of the inverter also accepts new setpoints with a 1-second resolution. The retrieved data is then collected via MQTT and stored in an InfluxDB.

TABLE I. EQUIPMENT OF THE EXPERIMENTAL BUILDING

Equipment	Details
BESS	$E_{max} = 19{,}5\ kWh$ $P_{\max\_charge} = 3\ kW$ $P_{\max\_discharge} = -3\ kW$ $t_{measurements} = 1\ s$ $t_{control\_delay} = 1\ s$
PV	$P_{\max} = 9.6\ kWp$

C. Experimental Setup

We ran the experiment over three consecutive days in May 2024, starting on Saturday, May 4th at midnight (UTC+2) and ending on Tuesday, May 7th at midnight (UTC+2). The initial State of Energy (amount of energy stored in the BESS) estimation and the first schedule were generated on the preceding Friday, May 3rd, at noon (UTC+2).

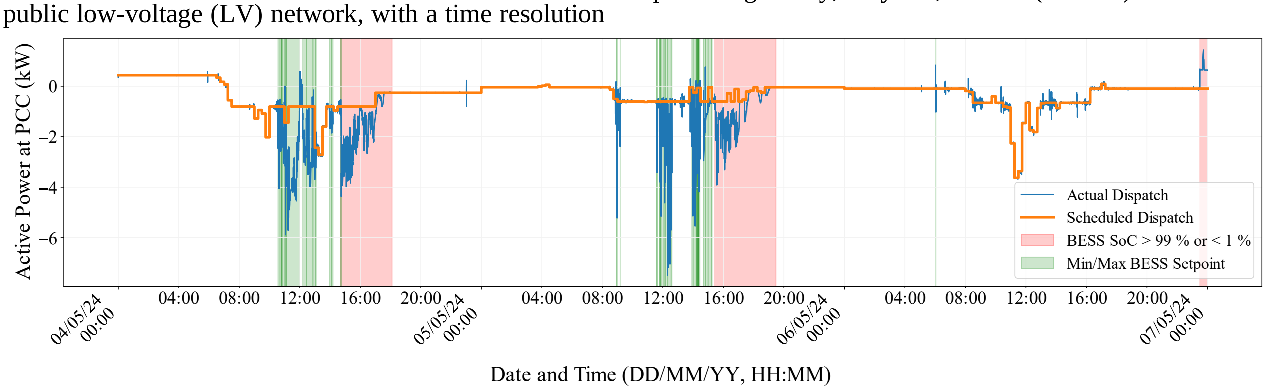

Fig. 4: Dispatch at the Point of Common Coupling (PCC) and the relation to the BESS and its State of Charge (SoC).

D. Case Study Results

As shown in Fig. 4, the results show that the schedule is mainly followed, and real-world effects in combination with energy management are becoming evident. Fast changes, visible mainly in the deviations from the schedule, are related to weather phenomena influencing the PV generation, such as clouds. The fast fluctuation could not be fully compensated by the BESS. The feed-in schedule is exceeded when the maximum BESS charging power is surpassed or capacity limits are reached, as indicated by the green or red shading respectively. The excess power is fed into the grid; therefore, the scheduled dispatch cannot be achieved.

A closer look at the 5th of May at 08:54 in Fig. 5 reveals several reasons why the scheduled dispatch cannot be followed precisely. Rapid changes in prosumption cause the BESS controller to balance the power exchange at the PCC ($\sum_{i=1}^{4} P_i$) to fulfill the schedule. However, delays in both the controller's response and the BESS's physical reaction lead to deviations on small time-scales. Additionally, as shown on the right side of Fig. 5, errors can also be a result of the BESS reaching its physical charging power limit, even though its nominal maximum of 3 kW is not yet reached.

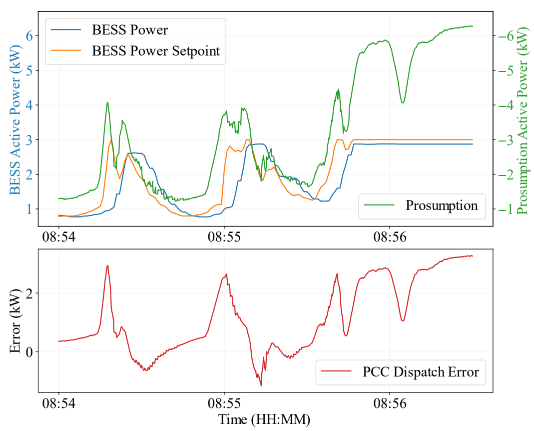

Fig. 5: Active Power of the BESS (top) and the resulting error of the prosumption at the PCC compared to the planned schedule at a 200 ms resolution (bottom).

Fig. 6 reveals a high Mean Average Error (MAE) from the dispatch schedule for the first two days, which can be derived from multiple reasons, such as a poorly forecast resulting in a poorly fitting dispatch schedule and high oscillations caused by a mixture of cloudy and sunny weather.

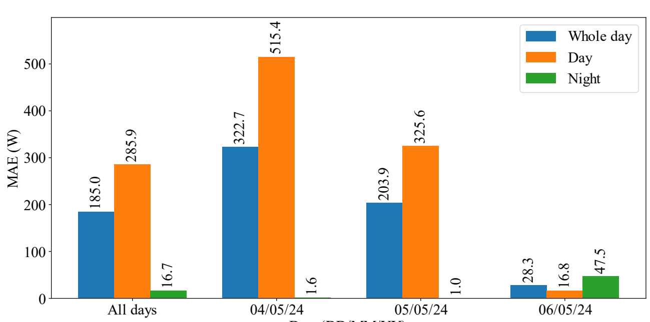

Fig. 6: MAE of the executed DF optimization with a time resolution of 10 s for calculating the MAE.

E. Discussion of the Real-World Applicability of the Dispatchable Feeder Optimization Problem

The observations highlight several aspects that can work against the objective of the DF, namely, strict adherence to the predefined schedule. While the DF strategy is designed to follow the schedule as closely as possible, non-idealities in real-world systems, such as latency, measurement inaccuracies, limited actuator precision, or unexpected behavior in components, can lead to deviations. This underscores a key challenge: achieving minimal schedule deviation becomes difficult when combining such an EMS strategy under real-world conditions. Therefore, this encourages the need for flexibility to better compensate for the deviations.

IV. Discussion

BEOP enables the monitoring of real-world effects and supports the validation and justification of EMS under real-world conditions.

To accommodate a broad range of EMS strategies, the framework has been designed with modularity and flexibility in mind. The optimization problem, which is central to many EMS implementations, can be easily exchanged, and forecasting services can be adapted to specific use cases or data sources. On the hardware side, the controller logic can be adjusted, control variables modified, and flexible assets reconfigured or reassigned. This adaptability allows for diverse experimental scenarios, including coordinated operation of multiple households or the implementation of decentralized strategies by individual agents within a hybrid environment comprising both real and simulated components.

Although the framework is closely integrated with the Energy Lab's hardware infrastructure, using open interfaces, particularly via MQTT, ensures that it can be adapted for deployment in other research facilities with minimal effort.

The modular, service-oriented architecture of the framework inherently introduces communication delays. However, these delays remain minimal and are negligible when compared to those of commercially available components, which often exhibit response times in the range of several seconds. This design choice enables responsive system behavior without sacrificing modularity or extensibility.

Nonetheless, the interaction with pure power hardware presents specific challenges. When such hardware components require communication to operate, they can introduce significant timing delays. These delays not only affect real-time system performance but can also lead to deviations between the actual power output and the intended setpoints. This underlines the importance of considering communication-induced latencies in hybrid EMS implementations and highlights the trade-offs between control precision and system complexity.

Furthermore, with suitable hardware, additional phenomena can be represented, such as multiple households acting in unison or individual households implementing their own strategies while interacting with both simulated and hardware networks. This approach could emphasize and expand future possibilities for capturing diverse perspectives on topics such as grid stability.

V. Conclusion and Future Work

The concept of the BEOP framework emerged from the need to validate EMS strategies in applications involving real hardware. The proposed framework enables a systematic investigation of the challenges associated with real-world energy management systems, offering scalability and flexible expandability with respect to components, forecast models, and optimization problems. The case study highlights both the potential of BEOP and the need for real-world validation of EMS strategies. Future work with BEOP will focus on validating additional approaches, such as rule-based control and reinforcement learning. The objective is to measure and quantify the intended goals of each EMS strategy and assess how well these goals are achieved under real-world conditions.

Moreover, while the current focus is on single-building applications, BEOP could serve as the foundation for simultaneous EMS execution across multiple buildings. This would open opportunities for research on collective behavior, for example, within the context of real-time price dynamics and their impact on grid-related effects. Such studies could be carried out using Power Hardware-in-the-Loop (PHIL) systems and real power components available at the Energy Lab infrastructure.

Declaration

During the preparation of this work the authors used ChatGPT in order to improve clarity and fluency during the writing process. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Contributions according to Credit, https://credit.niso.org/:

Conceptualization: S.B., M.B., A.N., S.W.; Methodology: S.B., M.B., A.N., T.M.; Software: S.B., M.B., A.N., J.P., T.M.; Investigation: S.B., M.B., A.N.; Data curation: S.B., M.B., A.N.; Writing - original draft: S.B., M.B., J.G., J.P.; Writing - review and editing: S.B., M.B., J.G., J.P., K.F., F.W., S.W., R.M., V.H.; Visualization: S.B., M.B.; Supervision: S.W., R.M., V.H.; Funding acquisition: V.H.

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