Experimental Multi-site Testbed for Advanced Control and Optimization of Hybrid Energy Systems

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***Abstract*—This paper presents a hybrid energy system (HES) experimental testbed developed at the University of Vermont, featuring a dual-site architecture that integrates on-campus laboratory facility with an off-campus solar and meteorological station. This supports the prototyping and validation of advanced HES control and optimization strategies. The platform integrates hardware-in-the-loop (HIL) simulations with a reconfigurable set of kVA-scale assets. A unified monitoring and communication architecture supports real-time data acquisition, model validation, and control implementation. The capabilities of the testbed are demonstrated through an HIL experiment in which a battery systems participate in solar PV smoothing.**

***Index Terms*—Experimental testbed, hardware-in-the-loop validation, hybrid energy systems, PV smoothing.**

I. Introduction

The global transition toward sustainable energy has accelerated renewable energy deployment. However, the inherent variability and uncertainty of these resources challenges grid reliability, flexibility, and power quality [1]. Hybrid Energy Systems (HES) have emerged as a promising solution to address the growing global demand for reliable, efficient, and sustainable power. HES integrate diverse energy resources, such as intermittent renewable sources like photovoltaic (PV) and wind generation, energy storage, and controllable loads including electrolyzers, electric vehicle (EV) charging stations, or data centers to enhance flexibility and reliability compared to standalone systems [2]. This has driven the rapid expansion of HES installations in the United States [3].

Deploying HES at scale introduces new layers of operational and control complexity, including power converter interactions, energy and ramping constraints, coupled dynamics, and multi-timescale coordination [4]. Most existing research is either limited to pairs of HES components (e.g., PV+X) or relies on mathematical modeling and simulation. Consequently, these studies are primarily evaluated based on model accuracy, computational efficiency, and numerical solvers. Furthermore, these models often fail to capture nonlinear switching effects, communication delays, and hardware limits. Conversely, full-scale field testing is often infeasible due to cost, safety issues, and complexity. This creates a validation gap, highlighting the need for intermediate methodologies combining hardware testing fidelity with laboratory controllability and safety [5].

Laboratory-based testbeds bridge this validation gap by providing controlled and repeatable environments to study complex device interactions. Hardware-in-the-loop (HIL) simulation has become critical for these validation efforts. In an HIL configuration, physical hardware components are interfaced with real-time digital simulations to enable systematic evaluation of device and controller performance and system-level stability before field deployment. A multi-site HIL testbed refers to geographically separated facilities that exchange measurements and/or setpoints to support coordinated experiments. Such architectures can combine laboratory controllability with field realism, however they also introduce additional communication and integration requirements compared to single-site setups [6]. Several HIL testbeds have been developed that address different aspects of HES validation and inverter-dominated grid integration, as summarized in Table I. While these facilities demonstrate valuable capabilities, most platforms emphasize either large-scale integration or single-facility component validation. Therefore, there remains a need for reconfigurable, intermediate-scale platforms that are multi-site and can incorporate field measurements into laboratory HIL studies, enabling multi-timescale HES control validation under real-world conditions.

This paper presents a new multi-site HES experimental testbed at the University of Vermont (*The Accelerated Testing Lab*), designed for the prototyping and validation of advanced control and coordination strategies for grid services. Compared to existing testbeds (Table I), the platform uniquely combines:

- A dual-site architecture integrating off-site field PV and weather data with on-campus hardware assets and HIL,
- A reconfigurable HES platform with PV, batteries, inverters, and electrolyzer with plug-and-play interfaces,
- A unified framework for multi-timescale HES control and real-time data streaming.

This paper provides a comprehensive overview of the key capabilities and features of this testbed, and experimentally validates battery participation in solar smoothing as a representative test case. The validation is conducted through an HIL setup with a physical battery, simulated batteries, and a real-time controller. The remainder of this paper is organized

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TABLE I: Summary of selected North America testbeds and their key assets and capabilities

Testbed	Location	Scale	Key Assets	Capabilities	HES Integration	Multi-site
Energy System Integration Facility (NREL) [7]	Colorado	1 MW	Power converters, batteries, electrolyzer, and fuel cell	HIL validation, power management evaluation, power system emulation, and microgrid control.	Yes	Yes
HIL Platform (North Carolina State University) [8]	North Carolina	250 kW	PV and power converters	MPPT implementation, voltage and frequency control, grid emulation, and HIL validation.	No	No
FIU testbed (Florida International University) [9]	Florida	40 kW	AC generators, power converters, adjustable loads, and SCADA system	PV and wind emulation, HES AC/DC control, energy management, and MPPT implementation.	Limited	No
SSMTB testbed (Sandia) [10]	New Mexico	30 kW	Diesel generators, energy storage, and programmable loads	PV and wind emulation, voltage and frequency control, and HIL validation.	Limited	No
UTA testbed (University of Texas-Arlington) [11]	Texas	15 kW	PV, wind turbine, fuel cell, battery, power converters, and loads	Power management, voltage and frequency control, and power quality analysis.	Yes	No
Multi-site networked HIL platform [6]	Three states (CO,NC,TN)	N/A	ADMS, protocol adapters, HIL sites	DER emulation, multi-site HIL evaluation of distributed control, and ADMS–DER coordination	No	Yes

TABLE II: Equipment Specifications

Component	Description	Specifications
PV Array	ET Solar	23.4 kW DC
Inverter	SolarEdge	3×10 kVA, single-phase
Battery (TBI 2026)	KORE Power	100 kW/233 kWh
LFP Battery	Enphase ACB 1.0	6×1.2 kWh, 26.5 V
NMC Battery	KORE Power	2×6.5 kWh, 59.6 V
Inverter	UNIFI reference design	4×5 kVA, 3-phase
Electrolyzer	Verde hydrogen	15 kW alkaline stack
DC Power Supply	Chroma 62120D-1200	12 kW, 0–1200 V, ±55 A
Regenerative Grid Simulator	Chroma 61812	12 kVA, 0–600 V
Microcontroller	TMDSCNCD28379D	100 MHz
Real-Time Simulator	Opal-RT OP5033	Intel® Xeon® (4 cores)
FPGA and I/O Expansion	Opal-RT OP4610	FPGA, 64 A/D I/O

as follows. Section II describes the HES laboratory design and HIL configuration of the testbed, including the electrical system architecture and data streaming framework. Section III details the key capabilities of the HES platform. Section IV presents an experimental test case, while Section V concludes the paper with perspectives on future work.

II. Experimental Testbed and System Architecture

The HES testbed features a distributed architecture composed of two physically distinct but tightly interconnected laboratory facilities:

- The Accelerated Testing Laboratory (ATL), the primary on-campus HIL platform.
- The Hybrid Solar Test Center (HSTC), an off-campus 23 kW solar and meteorological site with a planned battery system installation.

These facilities share real-time data, control signals, and HIL interfaces, enabling coordinated experiments that span devices, controllers, and grid-level scenarios. The overall system architecture is shown in Fig. 1, with key asset specifications in Table II. The design and capabilities of each facility are detailed in the following subsections.

A. Accelerated Testing Laboratory

The ATL at the University of Vermont (Fig. 1) integrates hardware and simulation capabilities to enable comprehensive testing of power electronics, energy storage, and control strategies in a reconfigurable cyber-physical environment. A bidirectional DC power supply feeds either two parallel-connected 5 kVA inverters or the batteries. The inverters, designed based on the UNIFI reference design [12], enable testing of advanced control strategies and the investigation of inverter dynamics

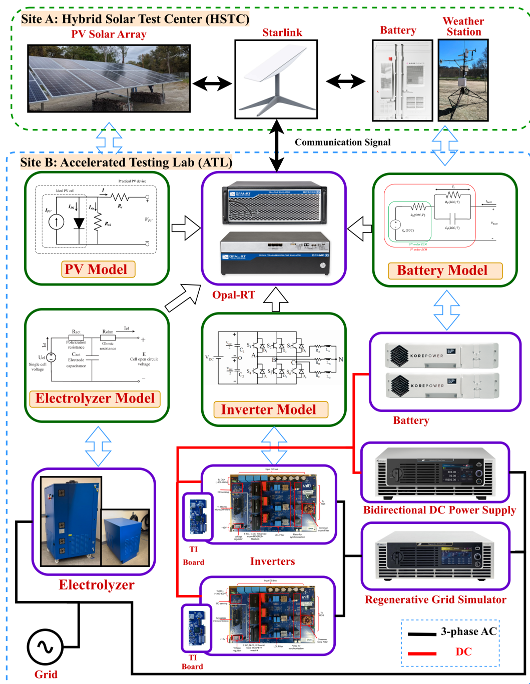

Fig. 1: Multi-site HES testbed with plug-and-play architecture. Components simulated in OPAL-RT can be replaced with physical ATL hardware (inverters, batteries, electrolyzer) or real-time HSTC field data (PV, weather) streamed via Starlink (Fig. 2), enabling flexible validation from pure simulation to HIL testing with real measurements.

and their impact on the grid. Each inverter is controlled by a Texas Instruments (TI) microcontroller, which enables the implementation of control strategies such as grid-forming (GFM) and grid-following (GFL) control, active/reactive power regulation, and coordinated multi-inverter operation. In addition, the DC power supply is connected to six 1.2 kWh Enphase LFP batteries, allowing for systematic charge, discharge, and storage co-optimization studies. On the AC side, the inverters are connected to a regenerative grid simulator (RGS). The testbed is coupled to a 15 kW electrolyzer, which represents hydrogen production as a controllable grid-interfaced load.

Furthermore, the Opal-RT simulator, with the OP4610 I/O expansion unit, provides the computational environment to emulate detailed grid behaviors. As shown in Fig. 1, the testbed

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architecture is explicitly designed for *plug-and-play* flexibility. This allows any component initially simulated within the Opal-RT to be seamlessly replaced by its physical hardware counterpart for full HIL validation. This creates a robust cyber-physical loop where Opal-RT issues analog setpoints to the RGS and bidirectional DC supply, which act as the physical interface to the device under test. These controllable power supplies generate the precise power and voltage conditions dictated by the real-time simulation. Voltage and current sensors capture responses from the hardware and feed them back to the Opal-RT's analog inputs, completing the HIL setup. This closed-loop configuration ensures that the real-time model dynamically reacts to physical hardware behavior and vice versa. This setup also facilitates integration of PV and weather profiles from the HSTC (discussed in the next subsection) to drive realistic validation scenarios.

B. Hybrid Solar Test Center

The ATL is supported by the HSTC located at the McNeil generating plant, one mile from campus. The HSTC hosts a 23 kW grid-connected solar PV array with SolarEdge inverters and an on-site weather station that records solar irradiance, temperature, wind speed, and humidity every 5 seconds, providing synchronized environmental and electrical data for PV modeling and performance analysis. A battery energy storage system (BESS) will be installed to enable field validation of battery-solar coordination strategies and grid services under real-world conditions.

C. Multi-site Communication and Data Integrity

The ATL and HSTC facilities are interconnected through a communication architecture that employs a Starlink satellite network for real-time data streaming and an on-campus server. As shown in Fig. 2, environmental and operational data from HSTC are measured using high-precision sensors and transmitted to a centralized server through Modbus coupled with a communication gateway. All data streams are time-synchronized and stored on the server for visualization and analysis, enabling real-time monitoring, control, and performance evaluation of HES subsystems.

While multi-site architectures offer significant advantages for HES research by integrating realistic field data with laboratory HIL capabilities, they also presents technical challenges that must be carefully managed. Communication latency between geographically separated sites can degrade closed-loop control performance, especially for fast-responding applications such as frequency regulation and voltage control, which require sub-second coordination. Precise time synchronization across sites is critical to maintain data integrity. Furthermore, integrating diverse components with different communication protocols (Modbus, CAN Bus) creates interoperability complexity. High-frequency measurements from distributed sensors also generate large data volumes that require robust infrastructure for time-aligned storage, real-time processing, and post-experiment analysis. The architecture in this paper addresses these challenges through a robust centralized server for high-volume data management, protocol-specific scripts

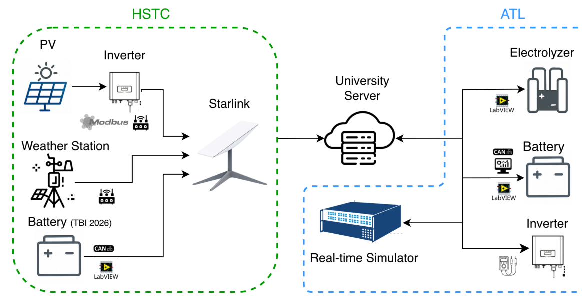

Fig. 2: Data-communication architecture for HSTC and ATL.

with built-in time synchronization for each communication standard, and direct data streaming via Starlink to reduce communication delays in control loops.

III. Platform Capabilities and Features

The experimental testbed provides a comprehensive environment for investigating HES integration and advanced control validation. The platform key capabilities span three interconnected domains:

- Component and system-level modeling and validation
- Control implementation and verification
- Hardware-in-the-loop (HIL) integration

This section describes the platform capabilities and their application to contemporary challenges in power system operation.

A. Component and system-level modeling and validation

Accurate models of individual HES components and their interactions are fundamental to enabling informed decision-making in system design, control development, and operational optimization. The ATL provides comprehensive experimental capabilities to validate physics-based and data-driven models across multiple components and timescales. The bidirectional DC power supply enables validation of battery models through controlled charge-discharge cycling, including the energy reservoir model [13] and electro-thermal equivalent circuit model [14] developed in prior work. Physics-based electrolyzer models describing hydrogen production rate, efficiency, and thermal dynamics have been validated through power cycling experiments on the 15 kW alkaline stack [15]. The platform also enables validation of efficiency-based and detailed switching inverter models. Data from the HSTC support PV model validation across diverse operating conditions and temperature dependencies. At the system level, aggregated circuit models capture interactions between PV, battery, and inverter systems through equivalent circuit modeling frameworks, facilitating state estimation and parameter identification [16]. These validated models form the foundation for multi-objective optimization and control studies.

B. Control implementation and verification

HES require coordinated controller design due to strong electrical and thermal coupling between components. As power systems become increasingly inverter dominated, traditional sources of inertia and voltage support disappear, and these services must be provided through tightly integrated,

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TABLE III: Capabilities of Multi-site Testbed

Grid Services	Time scale	Participating assets
Synthetic damping/inertia	$<$1s	Battery+Inverter
Voltage regulation	$<$60s	Battery/PV + Inverter
Frequency regulation	seconds-minutes	Battery/Coupled HES
Solar smoothing	seconds-minutes	PV+ Battery
Energy arbitrage & peak shaving	minutes-hours	Coupled HES

multi-layer control across HES components. Addressing these challenges requires experimental validation of advanced control and coordination strategies under realistic operating conditions. The ATL testbed bridges this gap by providing a flexible platform to validate control algorithms at component and system levels. At the component level, ATL enables direct implementation and testing of inverter and battery control algorithms, such as GFM and GFL modes, active/reactive power regulation, Volt-VAR control, and multi-inverter coordination, under programmable conditions including voltage sags, weak grid operation, and fault events. At the system level, the platform supports hierarchical and distributed control schemes, including model predictive control and economic dispatch-based coordination of batteries, PV, and electrolyzers. These validated control strategies enable the ATL to test algorithms for providing grid services, summarized in Table III. The shaded grid service is experimentally validated in this paper.

C. Hardware-in-the-loop (HIL) integration

HIL validation bridges the gap between simulation and field deployment by integrating real hardware with real-time digital simulation. It enables realistic evaluation of controllers, converters, and system interactions while maintaining safety and flexibility. The ATL testbed, equipped with an OPAL-RT real-time simulator and I/O unit, supports HIL configurations. The OPAL-RT simulator supports steady-state and dynamic grid models, enabling comprehensive evaluation of hardware interactions with the grid across different timescales. This enables detailed studies of inverter–grid interactions, coordination among HES components, and validation of advanced control strategies under realistic operating scenarios.

IV. Experimental Test Case: Solar Smoothing using Physical Battery Storage

The increasing penetration of PV generation introduces rapid power fluctuations from cloud transitions and irradiance variability, which challenges grid stability and power quality. A BESS can mitigate these fluctuations through fast response and bidirectional power capability, absorbing excess power during PV spikes and injecting power during drops. By coordinating PV generation with BESS operation, HES can smooth the power delivered to the grid. Grid operators impose ramp rate limits to keep fluctuations within acceptable ranges, defined as:

$$\text{Ramp Rate: } RR(t) = \frac{P_{\text{PV}}(t) - P_{\text{PV}}(t-\Delta t)}{\Delta t \cdot P_{\text{rated}}} \times 100 \quad (1)$$

where $P_{\text{PV}}(t)$ is the PV power at time t, Δt is the time interval, and P_{rated} is the rated PV capacity. In this study, the maximum

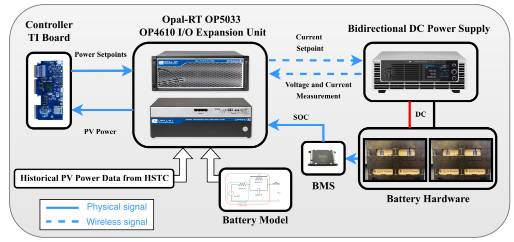

Fig. 3: Experimental setup for solar smoothing HIL validation showing two series-connected Enphase batteries with a BMS, bidirectional DC power supply, TI control card, and OPAL-RT real-time simulator.

allowable ramp rate is set to ± 10 %/min, consistent with limits specified in PV grid codes [17].

To evaluate the smoothing capability at ATL, an HIL experiment was conducted using the experimental setup shown in Fig. 3. The experiment uses historical 5-second PV power data from the HSTC site. To meet the power requirements for PV smoothing, the testbed integrates physical battery hardware (1.2 kW/2.4 kWh) together with three battery equivalent circuit models connected in series and implemented as the simulated battery (7.2 kW/7.2 kWh). The OPAL-RT sends PV power to the TI controller, which runs a 30-minute moving-average smoothing algorithm, detailed in Algorithm 1. An energy management system (EMS) distributes the required battery power between the two battery systems based on their maximum power ratings. The controller issues setpoints for the battery to the power supply through OPAL-RT. The battery management system (BMS) estimates the battery SOC.

Fig. 4 presents a two-hour snapshot of the HIL experiment. The raw PV power exhibits a maximum ramp rate of 56 %/min, significantly exceeding the ± 10 %/min grid limit. Fig.4(a) demonstrates that the BESS effectively reduces this to 9.45%/min. The simulation and experimental results show close agreement, with a root mean square error (RMSE) of 0.25 kW (2.4 % of maximum power). This error is attributed to communication latency, ADC quantization, sensor noise, and sampling effects. Fig. 4(b) presents dispatched battery power for the physical and simulated batteries. Fig. 4(c) shows the SOC of both batteries. The physical battery exhibits

Algorithm 1: PV Smoothing Controller

Input : $P_{\text{PV}}[k]$
Output: $P_{\text{batt,h}}[k],\ P_{\text{batt,s}}[k]$
Parameters: $N,\ T_s,\ w_h \leftarrow \frac{P_h^{\max}}{P_h^{\max}+P_s^{\max}}$; $w_s \leftarrow 1 - w_h$
$P_{\text{buf}}[i] \leftarrow 0,\ i = 1{:}N;\ k \leftarrow 1$ *// Initialization*
while *controller is running* **do**
  $P_{\text{buf}}[((k-1) \bmod N)+1] \leftarrow P_{\text{PV}}[k]$ *// 1) Insert new PV sample*
  $\hat{P}_{\text{PV}}[k] \leftarrow \frac{1}{N}\sum_{i=1}^{N} P_{\text{buf}}[i]$ *// 2) Smoothed PV power*
  $P_{\text{batt}}[k] \leftarrow P_{\text{PV}}[k] - \hat{P}_{\text{PV}}[k]$ *// 3) Total battery command*
  $P_{\text{batt,h}}[k] \leftarrow w_h \cdot P_{\text{batt}}[k]$ *// 4) Battery power allocation*
  $P_{\text{batt,s}}[k] \leftarrow w_s \cdot P_{\text{batt}}[k]$
  Output $P_{\text{batt,h}}[k],\ P_{\text{batt,s}}[k]$ *// 5) Output*
  $k \leftarrow k+1$, sleep(T_s)

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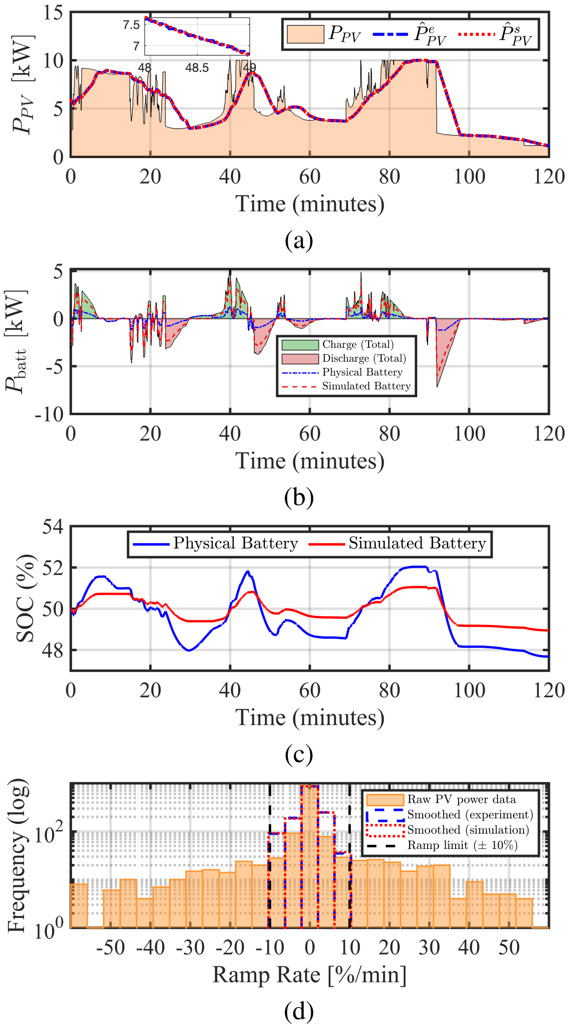

Fig. 4: Two-hour snapshot of HIL experimental PV power smoothing using 5-second HSTC data and the ATL battery setup. (a) Raw and smoothed PV power, where P_{PV} denotes the raw PV power, and $\hat{P}^e_{\mathrm{PV}}$ and $\hat{P}^s_{\mathrm{PV}}$ denote the experimentally measured and simulated smoothed PV power, respectively, (b) dispatched battery power of the physical and simulated batteries, (c) battery SOC, and (d) ramp-rate distributions.

larger deviations due to its lower capacity and maximum power; however, both batteries remain within safe operating limits. Fig. 4(d) illustrates the ramp rate distribution, showing reduced extreme events and zero grid-constraint violations. These results validate ATL's capability to implement and test PV smoothing strategies under multi-site operation.

V. Conclusion

This paper presented an experimental testbed for validating HES coordination and control strategies. The ATL platform integrates kW-scale PV, batteries, grid-tied inverters, and an electrolyzer with a real-time simulator. It enables modeling, control, and HIL validation of HES at both component and system levels. The solar smoothing experiment demonstrates ATL's ability to test grid-service control strategies.

Future work will use the OPAL-RT real-time simulator to coordinate all subsystems within a unified control and communication framework targeting diverse operational objectives. Another direction will focus on implementing and validating GFL and GFM control strategies under weak-grid and transient conditions. These advancements will further establish the ATL as a comprehensive real-time facility for accelerated research and deployment of next-generation HES.

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