Advancing Clean Energy Education through a Small Modular Reactor Simulator and Cross-Sector Collaboration

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Abstract

Preparing engineers to lead the clean-energy transition requires immersive learning environments that connect theoretical principles with operational realities. This paper presents a collaborative initiative among academia, industry, and state-level government stakeholders to establish a simulation-based nuclear energy laboratory centered on a Small Modular Reactor (SMR) Control Room Simulator. While commercial SMR deployment remains in early stages, the simulator provides an anticipatory workforce preparation platform enabling students to engage with grid-interactive nuclear operations, system dynamics, and safety-critical decision-making prior to plant commissioning. From a state workforce development perspective, early exposure to operational workflows and regulatory awareness is essential to ensuring readiness for emerging clean-energy infrastructure. The laboratory supports a senior-level power and energy systems lab course while also serving as a hub for workforce development, outreach, and professional training. Through scenario-driven operation of a virtual multi-module reactor, learners analyze system modeling, grid interaction, and operational workflows within a safe and controlled environment. The paper describes the partnership framework, curriculum integration, representative training scenarios, early evaluation outcomes, and alignment with state workforce objectives, offering a scalable model for integrating higher education, workforce preparation, and cross-sector collaboration in clean-energy education.

Keywords

Academia-Industry-Government Collaboration, Clean-Energy Education, Community Outreach, Simulation-Based Learning, Small Modular Reactors, Workforce Development

Introduction

The global transition toward low-carbon energy systems has intensified the demand for engineers who can integrate advanced generation technologies with increasingly complex power grids, evolving regulatory frameworks, and long-term sustainability objectives [1], [2]. Electric power systems are undergoing structural change driven by the rapid deployment of renewable energy resources, electrification of transportation and industry, growth in large-scale digital infrastructure, and heightened expectations for reliability and resilience. These developments require a workforce prepared to analyze, operate, and regulate hybrid energy systems that combine conventional, renewable, and emerging clean-energy technologies.

Small Modular Reactors (SMRs) have emerged as a promising component of this evolving energy landscape. Their modular design, siting flexibility, and potential for integration with renewable resources, industrial processes, and critical infrastructure position them as candidates for delivering firm, carbon-free power in both centralized and distributed applications [3], [4]. Although commercial SMR deployment remains in early stages, particularly within the United States, workforce preparation must precede widespread implementation. Similar to simulator-first approaches used historically in aerospace, grid operations, and advanced manufacturing, simulation environments can provide early exposure to operational workflows, regulatory context, and human-system interaction prior to full industrial deployment.

Traditional power and energy engineering curricula emphasize foundational theory in circuits, machines, control systems, and thermodynamics. While these elements remain essential, they often provide limited exposure to the operational environments in which advanced generation technologies are deployed. Graduates may possess strong analytical skills yet lack familiarity with control room workflows, procedural compliance, and real-time, team-based decision-making processes characteristic of nuclear and grid operations. This gap is particularly pronounced for electrical engineering students, whose engagement with nuclear systems is typically limited to grid interface considerations rather than integrated operational perspectives.

Simulation-based learning environments offer a scalable mechanism for addressing this gap [5], [6]. High-fidelity simulators enable learners to interact with realistic system models, observe dynamic responses to disturbances, and practice operational procedures in a safe and controlled setting. Recent engineering education studies further demonstrate that simulation and virtual-laboratory experiences, when paired with structured performance rubrics and pre- and post-assessment instruments, can improve students' operational decision-making, troubleshooting proficiency, and readiness for complex laboratory and field tasks [7], [8].

Beyond technical learning, immersive simulation environments also support the development of professional skills that are critical in safety-critical energy domains, including communication, coordination, and adherence to regulatory and organizational protocols. These competencies are increasingly emphasized by industry and workforce agencies as essential for early-career engineers entering highly regulated and digitally mediated operational environments. Importantly, simulation platforms enable interdisciplinary engagement by allowing students without formal nuclear engineering backgrounds to interact with system behavior and operational decision pathways while supported by targeted conceptual scaffolding.

In response to these educational and workforce needs, this paper presents a cross-sector initiative that leverages an SMR Control Room Simulator as the core of a clean-energy education and workforce development strategy. The project integrates academic instruction, industry participation, and government support to create a laboratory and training hub that aligns higher education, professional development, and community outreach within a unified framework. Through this effort, the work contributes (i) an interdisciplinary curriculum integration model, (ii) representative scenario-based training modules linking nuclear and grid operations, and (iii) a scalable partnership framework supporting anticipatory workforce preparation for emerging clean-energy technologies.

Partnership Framework and Development Process

Tri-Sector Collaboration Model

The laboratory initiative was developed through a structured partnership among three stakeholder groups: university faculty and academic leadership, industry partners from the nuclear and power sectors, and state-level energy and workforce development agencies. This tri-sector collaboration ensured alignment between educational objectives, workforce priorities, and regional energy strategy.

Academic partners led instructional design, competency mapping, assessment development, and integration into existing degree programs. Faculty oversight ensured alignment with accreditation requirements, institutional learning objectives, and disciplinary rigor while maintaining flexibility for interdisciplinary engagement.

Industry collaborators provided operational insight, scenario validation, and guidance on professional competencies expected of early-career engineers. Through curriculum consultations and scenario review workshops, industry participants helped ensure that simulator exercises reflected realistic operational challenges while remaining accessible for educational use.

The Virginia State Government partner contributed a perspective on workforce development needs, regulatory considerations, and policy frameworks associated with clean-energy deployment. Their involvement supported the integration of industry-relevant competencies and awareness of licensing and operational contexts within the instructional design.

Government Perspective on Workforce and Regulatory Alignment

From a Virginia workforce and energy development perspective, anticipatory training models are no longer optional; they are essential to keeping pace with the scale and speed of emerging electricity demand. In many regions, we are seeing a step-change in load growth driven primarily by hyperscale data centers, electrification, and advanced manufacturing. This growth is happening on timelines that consistently outpace traditional generation development and siting processes, creating a widening gap between infrastructure needs and operational readiness.

As the Commonwealth works to maintain reliability while advancing decarbonization goals, firm, dispatchable, carbon-free resources are increasingly becoming central to planning conversations. Advanced nuclear technologies, including SMRs, are often part of that discussion given their ability to provide reliable power at scale, particularly for large, concentrated loads. At the same time, successful deployment is not just a function of technology or capital. It depends heavily on having a workforce that is prepared to operate within highly regulated, safety-critical environments from day one.

Nuclear energy provides clean, firm, and reliable power aligned with the needs of emerging energy-intensive sectors such as advanced manufacturing and large-scale data centers. With capacity factors approaching 90%, nuclear generation significantly exceeds other technologies in delivering consistent, dispatchable power independent of weather conditions, while complementing variable renewable resources. This operational reliability positions nuclear energy, particularly advanced reactor designs such as SMRs, as a strong candidate for scalable deployment and a priority for utilities, states, and regional grid operators [9].

Beyond system reliability, the nuclear energy sector also plays a critical role in workforce and economic development. Nuclear facilities typically provide high-quality, stable employment, with wages averaging approximately 30% above national means and individual sites supporting hundreds of permanent positions. At the same time, the current nuclear workforce is aging, creating an urgent need to invest in workforce pipelines aligned with anticipated infrastructure expansion. Strategic investment across the nuclear value chain—from human capital development to supply chain readiness and plant construction—can signal long-term policy and market stability while strengthening academic–industry engagement.

With projections indicating the potential deployment of hundreds of small modular reactors over the coming decades, and with applications spanning grid support, industrial processes, electrification, and national security, embedding workforce training within academic frameworks becomes increasingly important. Coordinated collaboration among academia, industry, and government enables alignment of technical rigor, practical application, and regulatory readiness, supporting the development of a resilient and scalable nuclear energy ecosystem [10].

Workforce readiness, therefore, must develop in parallel with infrastructure planning. That includes familiarity with control room operations, procedural discipline, safety culture, and the interaction between generation assets and bulk power systems. In organized wholesale electricity markets, there is an added layer of complexity, interconnection processes, resource adequacy and capacity accreditation frameworks, and evolving reliability constructs, all of which shape how and when new resources come online. Engineers entering this space need exposure to both system operations and these broader market dynamics.

Simulation-based training platforms provide a practical way to accelerate that readiness ahead of commercial deployment. By giving students early exposure to operational workflows, alarm management, team-based decision-making, and grid-interactive behavior, these platforms help bridge the gap between academic preparation and real-world system operation. This is particularly important in the nuclear sector, where access to physical facilities is limited and most operational experience traditionally comes much later in the training pipeline.

Beyond workforce preparation, these types of environments also support broader economic development objectives. States that can demonstrate a capable and scalable talent pipeline are simply better positioned to attract capital-intensive energy infrastructure and energy-dependent industries. For advanced nuclear and data center development in particular, workforce readiness is increasingly a differentiator in site selection decisions.

The SMR Control Room Simulator laboratory aligns well with these priorities by embedding operational awareness, systems-level thinking, and professional discipline into engineering education. Through collaboration among academic, industry, and public-sector stakeholders, this model offers a practical and replicable framework for aligning workforce development with long-term energy strategy, reducing deployment risk, and strengthening regional competitiveness in an increasingly energy-constrained environment.

Looking ahead, Virginia is well-positioned to build on this model as part of a broader strategy to align workforce development with the Commonwealth's evolving energy and economic landscape. As demand for reliable, large-scale power continues to grow, particularly from data centers and other energy-intensive industries, the ability to pair infrastructure development with a trained, deployment-ready workforce will be increasingly important. Expanding simulation-based training, strengthening partnerships between universities and industry, and integrating workforce planning into energy policy can help ensure that Virginia not only keeps pace with growth, but also leads in the development and deployment of next-generation energy systems. In that context, this initiative represents more than a single program; it provides a scalable framework that can be extended across the Commonwealth to support long-term reliability, competitiveness, and clean-energy leadership. This alignment between infrastructure development and workforce readiness underscores the importance of simulation-based educational platforms as enabling technologies for policy-informed engineering education.

Co-Design and Iterative Development

The initial simulator experiments and operational scenarios were developed by industry partners to reflect authentic plant workflows, system responses, and operator training practices. These foundational modules provided realistic representations of normal, abnormal, and emergency evolutions within a multi-module SMR environment.

Building upon this industry-developed framework, the university translated and expanded the scenarios into a structured academic curriculum aligned with course-level and program-level learning outcomes. Faculty conducted competency mapping to connect simulator capabilities with engineering concepts in power systems, control theory, and energy conversion. Learning objectives were refined to ensure accessibility for electrical engineering students while preserving operational realism and safety-relevant context.

Draft laboratory modules were subsequently evaluated through collaborative design review involving representatives from industry and state-level stakeholders. Feedback focused on scenario sequencing, assessment criteria, instructional scaffolding, and regulatory awareness. Based on this input, the university iteratively refined laboratory instructions, debrief structures, performance rubrics, and reflection components to support measurable learning outcomes.

This co-development process produced a curriculum that integrates industry-authentic simulator exercises with academic rigor, balancing theoretical depth and operational authenticity while enabling continuous improvement across course offerings.

Laboratory Infrastructure and Technical Platform

The laboratory infrastructure centers on a multi-module SMR control room simulator capable of emulating reactor physics, thermal-hydraulic behavior, electrical generation, and grid interaction. The platform is based on the NuScale Energy Exploration Center simulator, which represents a multi-unit small modular reactor plant environment with an integrated control room interface designed using human factors engineering principles. The simulator is designed to represent functional characteristics common across advanced reactor concepts while preserving operational realism and supporting technology-neutral instruction. Figure 1 illustrates the SMR control room simulator environment used for instructional delivery.

Figure 1. SMR Control Room Simulator used in the simulation-based clean-energy laboratory

The simulator supports both single-module and coordinated multi-module operation, enabling students to analyze system behavior at both the unit and system levels. The simulated plant architecture includes up to twelve reactor modules and integrates core physics, balance-of-plant, and electrical system models operating concurrently to represent plant-level dynamics.

The technical platform includes:

- High-Fidelity Reactor Models: Real-time simulation of core power behavior supported by coupled physics and thermal-hydraulic modeling.
- Thermal-Hydraulic and Balance-of-Plant Models: Integration of RELAP-based module dynamics with plant systems and turbine–generator behavior.
- Electrical Power System Models: Generator, excitation, and grid interconnection models supporting voltage and frequency regulation studies.
- Human System Interface (HSI): A custom integrated interface providing operator controls, plant indications, navigation tools, and multi-module overview displays.
- Process Library and Automated Procedures: A digital repository of normal, abnormal, and emergency procedures enabling scenario-based training and automated operational sequences.
- Tiered Notification and Alarm System: Structured alarms, cautions, and notices supporting prioritization of operator response and situational awareness.
- Instructor Station: A dedicated interface for initiating transients, resetting scenarios, and managing simulator execution during instructional sessions.
- Remote Access Infrastructure: Secure network environments supporting hybrid and professional training delivery.

The human–machine interface supports navigation across system displays, module overview pages, event logs, and safety monitoring dashboards, allowing learners to interact with plant parameters and procedures in a manner consistent with contemporary digital control room design. The interface incorporates safety function monitoring related to containment integrity, reactivity control, and core heat removal, reinforcing system-level safety awareness during both normal and abnormal conditions.

To ensure technical accuracy and educational relevance, simulator configuration and instructional modules were developed with input from industry practitioners and nuclear engineering subject-matter experts. This collaborative validation process helped align simulated behaviors with accepted operational principles while maintaining accessibility for electrical engineering learners.

This configuration allows the laboratory to support undergraduate instruction, professional training, and outreach activities without requiring physical access to nuclear facilities. Given regulatory and security constraints associated with plant-based training, the simulator-first approach provides a scalable pathway for introducing operational workflows, human–machine interaction, and decision-making under dynamic conditions within an academic setting.

Curriculum Alignment and Learning Objectives

Curriculum integration was guided by a competency-mapping process that aligned simulator features with course-level and program-level learning outcomes. Faculty identified core competencies across three domains:

- Technical Competence: System modeling, grid interaction, thermal-hydraulic behavior, and protection system response.
- Operational Decision-Making: Procedural compliance, fault response, and coordination under time-varying conditions.
- Professional Skills: Communication, teamwork, and documentation aligned with regulatory and organizational standards.

The simulator laboratory is formally implemented as ECE 408 – Small Modular Reactor Simulation Lab, a structured semester-long course progressing from foundational simulator proficiency to complex emergency evolutions and integrated crew audits.

Early sessions focus on general simulator navigation, conduct of operations principles, and human–machine interface proficiency, including alarm management, trending of reactor parameters, and equipment manipulation. These sessions establish baseline competence in simulator controls and plant indications.

The curriculum then advances through sequenced "normal evolutions," including controlled reactor power reductions, turbine bypass operation, reactor shutdown and cooldown, and reactor startup procedures. These activities connect core theoretical knowledge from circuits, control systems, and thermodynamics to plant-level operational behavior.

Subsequent modules introduce abnormal evolutions such as small loss-of-coolant events, condenser vacuum loss, control rod malfunctions, and seismic-induced loss of offsite power. Students interpret plant response, manage alarms, and apply procedural guidance to stabilize plant conditions.

Emergency evolutions further require students to respond to design-basis loss-of-coolant events, steam generator tube failures, and Anticipatory Trip Without Scram (ATWS) scenarios. These scenarios explicitly reinforce nuclear safety principles related to containment isolation, reactivity control, and core heat removal.

The competency framework was developed through an interdisciplinary lens to support electrical engineering students engaging with nuclear-system operation. Rather than providing a full nuclear engineering curriculum, the instructional design emphasizes system integration, control logic, and human–machine interaction supported by targeted conceptual scaffolding.

Preparatory materials introduce foundational concepts in reactor kinetics, safety-function monitoring, and defense-in-depth philosophy sufficient for students to interpret simulator behavior during normal, abnormal, and emergency conditions.

The semester culminates in an Integrated Crew Audit Scenario, during which students operate in mixed-role teams to execute full plant scenarios requiring coordinated communication, procedure adherence, and time-critical decision-making. Performance is assessed through laboratory reports (85%) and a comprehensive final project (15%), reinforcing accountability and technical reflection.

Through this structured progression, students connect theoretical knowledge from power systems, control theory, and energy conversion courses with realistic operational contexts while developing professional conduct aligned with nuclear industry expectations.

Representative Training Scenarios

To illustrate the instructional value of the simulator laboratory, representative training scenarios were selected from the structured sequence implemented in ECE 408 – Small Modular Reactor Simulation Lab. These scenarios reflect progression from normal operation to abnormal and emergency conditions while reinforcing both technical and professional competencies.

Scenario 1: Reactor Startup and Controlled Power Reduction

Early instructional modules guide students through reactor startup and controlled power maneuvering under stable grid conditions. Learners operate simulator controls, monitor plant parameters, and execute procedural steps associated with reducing reactor power from full output to partial load. This scenario emphasizes interpretation of trending data, alarm prioritization, and coordination between reactor and turbine control actions. Debrief sessions focus on understanding system coupling and the operational trade-offs associated with load-following behavior.

Scenario 2: Abnormal Event Response – Small Loss-of-Coolant Event

In intermediate modules, students respond to a simulated small loss-of-coolant event. Acting in role-based teams, learners interpret alarms, diagnose plant conditions, and implement abnormal operating procedures to stabilize system parameters. This scenario reinforces situational awareness, alarm management, and procedural compliance while highlighting safety functions related to containment integrity and core cooling. Instructor feedback identified initial student difficulty in prioritizing concurrent alarms, leading to the introduction of structured alarm triage guides and pre-briefing enhancements.

Scenario 3: Emergency Event Response – Design-Basis Loss-of-Coolant Event

Advanced sessions require teams to manage design-basis loss-of-coolant scenarios involving rapid plant transients and safety system activation. Students coordinate reactor trip actions, containment isolation, and emergency procedure execution while documenting decision pathways. The scenario emphasizes human–system interaction under time pressure and demonstrates the role of defense-in-depth principles in nuclear safety. Iterative refinement of this module resulted in expanded debrief discussions focused on communication clarity and documentation practices.

Integrated Crew Audit Scenario

The semester culminates in a comprehensive integrated scenario in which students assume mixed operational roles and execute full-plant response sequences combining normal, abnormal, and emergency elements. This capstone experience reinforces teamwork, communication protocols, and procedural discipline while enabling instructors to evaluate students' holistic understanding of plant operation and safety management.

A summary of representative training scenarios and associated learning objectives is provided in Table I.

Table I.

Representative Training Scenarios and Learning Objectives

Scenario	Operational Focus	Key Skills Developed	Instructional Purpose
Reactor Startup & Power Maneuvering	Load-following and coordinated plant operation	Parameter interpretation, alarm prioritization, coordination	Connect theoretical power system behavior with operational decision-making
Small Loss-of-Coolant Event	Abnormal condition diagnosis and response	Alarm management, procedural adherence, situational awareness	Reinforce safety function awareness and abnormal procedure execution
Design-Basis Loss-of-Coolant Event	Emergency response and safety system activation	Team communication, decision-making under stress, documentation	Demonstrate defense-in-depth and emergency procedure coordination
Integrated Crew Audit Scenario	Full plant operation with mixed conditions	Role-based teamwork, procedural discipline, systems thinking	Evaluate holistic understanding of plant operation and safety management

Institutional Setting and Implementation Context

The SMR Control Room Simulator laboratory is embedded within ECE 408 – Small Modular Reactor Simulation Lab, a senior-level course serving upper-division electrical engineering students. The course is delivered in a dedicated simulator environment at the Arlington campus and meets weekly in extended laboratory sessions of approximately 2.5 to 3 hours.

Enrollment during the pilot offering was intentionally limited to a small cohort to support immersive, team-based interaction and close instructional supervision within the control room setting. Students entered the course with prerequisite knowledge from circuits, control systems, and physics coursework, providing foundational preparation for engaging with simulator-based operational tasks.

Students participate in a structured sequence of simulator sessions progressing from system familiarization to multi-variable operational scenarios involving grid disturbances, abnormal plant behavior, and emergency response. Each session follows a consistent instructional cycle: (i) pre-briefing and technical framing, (ii) scenario execution in assigned operational roles, and (iii) guided debrief.

Role assignments reflect authentic control room organization, with students rotating through positions such as reactor operator, turbine operator, safety analyst, and documentation lead. This structure promotes interdisciplinary communication, shared situational awareness, and accountability in procedural execution.

Participants enter the course with varied academic backgrounds in power systems, control theory, and thermal sciences. To accommodate this diversity, preparatory modules and reference materials are provided prior to simulator engagement, including short technical primers and walkthrough videos. This scaffolding approach ensures that students can engage productively with complex operational tasks regardless of prior exposure to nuclear or grid-interactive systems.

Assessment in the pilot implementation was based primarily on laboratory reports documenting scenario execution and analysis, complemented by a final project synthesizing operational insights across scenarios. This structure reinforced reflection, technical documentation, and systems-level reasoning as core learning outcomes.

Limitations

While the SMR Control Room Simulator laboratory provides a high-fidelity environment for experiential learning, its design and implementation are shaped by several institutional and practical constraints that influence both scope and evaluation.

First, access to physical nuclear facilities for instructional purposes remains highly restricted due to regulatory, safety, and security requirements. As a result, the simulator-first approach was adopted not as a replacement for plant-based training, but as a pragmatic and scalable alternative that enables early-stage exposure to operational workflows within an academic setting. The simulator is therefore positioned as an educational digital twin supporting conceptual understanding of plant behavior, human–machine interaction, and procedural reasoning rather than as a platform for operator licensing or plant-specific certification.

Second, the initial implementation has been conducted within a single institution and a limited cohort size, which constrains the generalizability of early evaluation findings. Class enrollments are intentionally capped to preserve meaningful team-based interaction within the control room environment, resulting in relatively small sample sizes for quantitative analysis. Consequently, early assessment results are interpreted as indicative rather than conclusive, and future work will prioritize multi-cohort and multi-institutional studies to strengthen external validity.

Third, simulator fidelity reflects functional representation rather than exact replication of a commercial SMR design. While the platform incorporates high-fidelity physics models and operational interfaces, instructional scenarios are adapted to emphasize learning objectives and may simplify plant configuration details to enhance pedagogical clarity.

Finally, scheduling and curricular integration present ongoing challenges. Aligning simulator-based modules with existing degree requirements, accreditation timelines, and professional training calendars requires coordination across departments and external partners. These logistical considerations shape the pacing and sequencing of laboratory activities and inform the modular design approach described in this work.

Acknowledging these constraints provides important context for interpreting early outcomes and highlights the conditions under which similar initiatives may be successfully adopted. At the same time, these limitations reinforce the value of cross-sector collaboration as a mechanism for sharing resources, expertise, and evaluation frameworks across institutions and regions.

Assessment and Evaluation Methodology

Learning Outcomes and Metrics

Assessment focuses on three primary dimensions: conceptual understanding, operational competence, and professional skill development. Metrics include performance on scenario-based tasks, quality of technical documentation, and team-based project outcomes.

Within the ECE 408 implementation, assessment was closely aligned with course deliverables, including laboratory reports documenting scenario execution and analysis (85%) and a final integrative project (15%). This structure emphasized reflective learning, technical communication, and synthesis of operational insights across normal, abnormal, and emergency scenarios.

To strengthen evidence of learning efficacy, the evaluation plan integrates multiple instruments commonly used in simulation-based engineering education:

(i) rubric-based assessment of scenario execution and operator communication;

(ii) pre- and post-concept checks targeting SMR operations, grid interaction, and safety-relevant decision pathways;

(iii) structured reflection prompts capturing changes in systems thinking and teamwork behaviors; and

(iv) evaluation of team-based design or analysis projects. This mixed-instrument approach aligns with simulation laboratory studies reporting stronger learning gains when authentic tasks are paired with explicit assessment rubrics and outcome measures [7], [8].

Scenario-based evaluation also incorporated instructor observation of role-based performance, including alarm prioritization, procedural adherence, and communication clarity. Debrief discussions following each session provided qualitative insights into student reasoning and areas for instructional refinement.

Preliminary Findings

Preliminary observations from the initial implementation suggest improvements in students' ability to connect theoretical models with operational behavior, increased confidence in team-based problem solving, and enhanced awareness of professional roles in nuclear and power system operations.

Student reflections highlighted growth in situational awareness, understanding of safety function interactions, and appreciation of the complexity of coordinated plant and grid operations. Instructor observations further suggested progressive improvement in alarm management and procedural execution across the semester.

Given the pilot cohort size, these findings are interpreted as formative indicators rather than statistically generalizable results. Ongoing and future implementations will incorporate larger cohorts and longitudinal tracking to evaluate sustained learning outcomes and career pathway influence.

Scalability and Replicability

The modular design of the simulator laboratory supports adaptation across institutional and regional contexts. Universities can align simulator scenarios with local energy priorities while preserving a consistent pedagogical framework.

The instructional architecture implemented in ECE 408 demonstrates how simulation-based nuclear and grid integration learning can be embedded within existing electrical engineering curricula without requiring the establishment of a full nuclear engineering program. Core learning modules, ranging from normal evolutions to emergency scenarios, can be adapted to alternative program structures while maintaining competency alignment.

Remote access capabilities enable distributed participation, allowing the laboratory to serve as a shared resource for multiple institutions and professional training programs [5], [6]. This feature supports hybrid instruction, cross-institution collaboration, and continuing education offerings without requiring participants to be physically co-located within the simulator facility.

From a resource perspective, simulator-based laboratories offer a cost-effective complement to plant-based training environments. Implementation primarily involves simulator licensing, visualization infrastructure, and instructional development rather than physical reactor hardware or access to operational facilities. This reduced infrastructure barrier enhances feasibility for institutions seeking to introduce advanced nuclear or hybrid energy education.

The model further supports shared scenario libraries, common rubric frameworks, and cross-institution benchmarking of learning outcomes. Collaborative development of instructional modules and evaluation tools can accelerate adoption and foster a community of practice around simulation-driven clean-energy education.

From a sustainability perspective, the model aligns with broader engineering education insights that emphasize

(i) measurable learning objectives,

(ii) authentic experiences integrating professional practice, and

(iii) ecosystem partnerships sustaining curricular relevance over time [11], [12].

Conclusion

This paper presents a simulation-based, cross-sector approach to advancing clean-energy education through the use of a Small Modular Reactor Control Room Simulator as both an instructional platform and a workforce development resource. By integrating academic coursework, professional training, and community outreach, the initiative demonstrates how immersive simulation environments can connect theoretical instruction and the operational realities of modern, low-carbon power systems.

Collaboration among the university, industry, and government partners enabled the development of technical modules that reflect evolving workforce needs while embedding regulatory and sustainability considerations into engineering instruction. Through scenario-driven learning, students strengthened both domain-specific competencies in power and nuclear systems and professional skills in teamwork, decision-making, and stakeholder communication.

The structured implementation within ECE 408 - Small Modular Reactor Simulation Lab illustrates how interdisciplinary simulation-based instruction can be embedded within electrical engineering curricula to provide anticipatory workforce preparation for emerging nuclear and hybrid energy technologies. By aligning academic instruction with industry validation and state workforce priorities, the model offers a replicable framework for strengthening regional clean-energy talent pipelines and supporting sustainable infrastructure readiness.

Findings from the pilot implementation suggest that simulator-driven laboratories can enhance students' situational awareness, procedural reasoning, and appreciation of safety-critical system operation while fostering collaborative professional behaviors aligned with industry expectations. Although early results are formative, they indicate the value of immersive digital environments for preparing engineers to engage with evolving clean-energy infrastructures.

Future work will expand participation through additional industry partnerships and introduce micro-credential pathways recognizing competencies in nuclear operations, grid interaction, and clean-energy system integration. Planned enhancements include multi-institutional collaborations, advanced policy and regulatory modules, and longitudinal studies examining the long-term influence of simulation-based learning on students' academic pathways and career development. Together, these efforts position the model as a scalable and replicable framework for aligning higher education, industry engagement, and government priorities in support of a resilient, future-ready clean-energy workforce.

Acknowledgment

This work was supported in part by the Virginia Clean Energy Innovation Bank and Virginia Energy, which funded the Small Modular Reactor Control Room Simulator and supported related workforce development activities.

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