Proceedings of the 11th North American International Conference on Industrial Engineering and Operations Management, Milwaukee, Wisconsin, USA, June 9-11, 2026

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA11.20260151
Published: June 9, 2026

A Comparative Survey of Immersive Learning for Operator, Maintenance, and Safety Training in Energy Systems

Nadia Anjum
Department of Industrial & Systems Engineering
Wayne State University
Detroit, MI, USA
nadiaanjum@wayne.edu

Sara Masoud
Assistant Professor
Department of Industrial & Systems Engineering
Wayne State University
Detroit, MI, USA
saramasoud@wayne.edu

Murat Yildirim
Associate Professor
Department of Industrial & Systems Engineering
Wayne State University
Detroit, MI, USA
murat@wayne.edu

Feng Qiu
Argonne National Laboratory
Lemont, IL, USA
fqiu@anl.gov

Abstract

Immersive learning (IL) technologies, including virtual, augmented, and mixed reality, have been increasingly adopted for training in energy systems, where high-risk, low-frequency events and hazardous operating environments limit the feasibility of real-world training. Over the past two decades, such approaches have been explored across nuclear, power grid, oil and gas, and renewable energy domains, yet the literature remains fragmented across applications and training objectives. This survey reviews IL for energy training from 2000 to 2025, focusing on four core priorities: (i) operator training, (ii) maintenance and field services, (iii) safety and emergency response, and (iv) education and workforce development. A cross-domain taxonomy that organizes prior work by energy domain, immersive modality, pedagogical approach, and evaluation maturity; enabling comparative analysis across sectors is introduced here. The survey highlights dominant design patterns as well as persistent gaps in evaluation rigor, particularly with respect to

© IEOM Society International

transfer of training to real-world performance. Finally, it is concluded by outlining research directions to support evidence-based, scalable, and trusted immersive training in energy systems.

Keywords
Immersive learning, Virtual reality, Augmented reality, Energy systems training.

1. Introduction

Immersive learning (IL) emerged as a powerful educational paradigm grounded in experiential and situated learning theories (Kuhail et al., 2022, Masoud et al., 2025). From a pedagogical perspective, IL emphasizes learning by doing (Kuhail et al., 2022). Learners actively engage in realistic environments, manipulate system components, and receive immediate feedback within contexts that closely resemble real-world practice (Kuhail et al., 2022, Masoud et al., 2022). This approach aligns with well-established principles of experiential learning, cognitive apprenticeship, and simulation-based instruction, where understanding is constructed through interaction, reflection, and iterative practice rather than passive content consumption (Kuhail et al., 2022). By enabling learners to experience situations that would otherwise be inaccessible, IL offers unique affordances for developing procedural knowledge, spatial understanding, and situational awareness.

These pedagogical advantages are particularly salient in the context of energy systems. Training in energy systems involves high-risk, low-frequency events and operations that are dangerous, costly, or impossible to practice in real settings (Lucas et al., 2018). Unlike most of the applications in general industrial training, energy systems are tightly coupled, safety-critical, and highly regulated, where errors can rapidly propagate and consequences affect human life, the environment, and infrastructure reliability. As a result, training places strong emphasis on procedural accuracy, coordination, and real-time decision-making under uncertainty. Traditional training methods often struggle to prepare personnel for such rare but consequential scenarios, whereas IL enables safe rehearsal, repeated practice, and enhanced situational awareness in realistic yet risk-free environments.

Over the past two decades, IL has been explored across a wide range of energy applications, including nuclear control-room training, power grid and substation operations, oil and gas maintenance and emergency response, and safety training for wind and other renewable energy systems. However, this body of work remains highly fragmented. Studies are often confined to specific domains (e.g., nuclear versus offshore wind), specific tasks (e.g., maintenance versus emergency response), or specific technologies, with limited cross-domain synthesis. Moreover, research communities addressing operator training, maintenance and field service, safety and emergency response, and workforce development have evolved in parallel, despite overlapping pedagogical goals and technological foundations. As a result, there is currently a lack of a unified synthesis that systematically examines how IL has been applied across the energy sector, how different training priorities relate to one another, and where evidence remains weak or inconsistent.

2. Background and Scope

2.1 Immersive Learning Technologies in Energy Systems

IL technologies can be situated along the reality–virtuality continuum (Skarbez et al., 2021), which ranges from fully physical environments to fully virtual ones. Within the broader category of extended reality (XR), technologies differ in the extent to which they replace or augment the real world and in the pedagogical roles they support in training. At the virtual end of the continuum, virtual reality (VR) provides fully simulated environments in which learners are immersed and largely isolated from the physical world. VR has been the dominant immersive modality in energy training, supporting simulation-based and experiential learning for applications such as control-room operation, substation procedures, refinery processes, turbine maintenance, and emergency response. By enabling repeated rehearsal of high-risk, low-frequency events, VR supports spatial understanding, procedural learning, and situational awareness without real-world danger. Closer to the physical end of the continuum, augmented reality (AR) overlays digital information onto real environments. In energy systems, AR is primarily used for maintenance and field service training, where in-situ procedural guidance, component highlighting, and visualization of hidden assets support just-in-time learning and reduce cognitive load during complex tasks. Mixed reality (MR) occupies an intermediate position on this continuum. Figure 1 provides a conceptual overview of how training technologies in the energy sector have evolved along the Reality–Virtuality continuum from 2000 to 2025. Early training paradigms are dominated by simulator-centric approaches designed to support procedural accuracy and certification in safety-critical environments. As immersive technologies matured, VR increasingly augmented and, in some cases, replaced traditional simulators for rehearsing hazardous and low-frequency scenarios. More recent developments emphasize VR-centric solutions

© IEOM Society International

with selective hybridization, including limited MR use for task support and digital-twin integration. Importantly, Figure 1 illustrates that adoption does not progress linearly toward greater physical–virtual integration; instead, energy-sector training selectively adopts technologies that balance realism, controllability, and assessment requirements. This technological progression reflects both hardware maturity and a growing alignment between immersive modalities and specific training needs within energy systems.

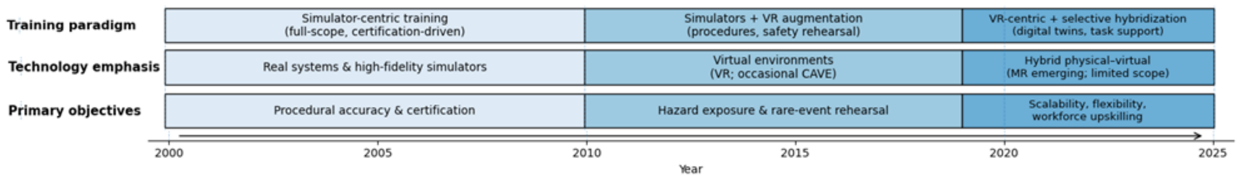

Figure 1. Conceptual evolution of energy sector Training Technologies (2000-2025)

2.2 Energy Training Context and Priority Areas

Training in energy systems operates under constraints that are fundamentally different from those in many other industrial or educational settings. Energy infrastructures are safety-critical, highly regulated, and often geographically dispersed, with operations that span control rooms, field environments, and emergency response contexts. Based on these characteristics and the patterns observed in the literature, this survey focuses on four primary priority areas.

Operator training includes control-room and field operators responsible for monitoring and controlling energy systems. In domains such as nuclear power, electric grids, and oil and gas processing, operators manage tightly coupled systems where errors can propagate rapidly under both normal and abnormal conditions. Immersive learning enables rehearsal of decision-making, coordination, and system interactions for rare, high-impact events that cannot be safely or economically practiced in real facilities.

Maintenance and field service training focuses on technicians who inspect, repair, and service energy infrastructure in hazardous or hard-to-access environments such as high-voltage substations, offshore platforms, wind turbine nacelles, and confined spaces. Immersive technologies, particularly AR, support procedural learning, spatial understanding, and task sequencing, helping reduce error and improve safety during hands-on work.

Safety and emergency response training prepares personnel to respond to accidents, failures, and extreme events, including fires, explosions, electrical faults, radiological incidents, and evacuations. Because these scenarios are high-risk and low-frequency, immersive learning enables repeated, risk-free exposure and rehearsal of coordinated responses, making it one of the most mature applications of immersive learning in energy systems.

Workforce training and education addresses pre-operational learners and workers entering, upskilling, or transitioning within the energy sector. Immersive learning supports safe familiarization with complex systems, foundational skill development, and the transition from classroom instruction to operational environments, helping build confidence and competence while reducing training time and risk.

2.3 Scope and Inclusion Criteria

This survey adopts a clearly defined scope to ensure coherence, rigor, and relevance. The timeframe covered spans 2000 to 2025, capturing the evolution of immersive learning (IL) in energy systems from early desktop-based simulations to contemporary VR, AR, and MR applications. This period reflects both technological maturation and shifts in pedagogical practice. The energy domains included in this review encompass fossil energy systems (e.g., oil, natural gas, refining, and coal-related operations), nuclear energy, and renewable energy systems, including wind, solar, hydropower, geothermal, and biomass where relevant training applications have been reported. This broad domain coverage allows for cross-sector comparison while acknowledging domain-specific constraints and practices. Finally, the review is explicitly focused on training and learning applications of immersive technologies. Included studies address educational objectives such as skill development, procedural training, and safety preparedness. Works that focus exclusively on pure visualization, design, or planning tools, without an explicit training or learning component, are excluded. Following these selection criteria, and after systematic screening, cleaning, and removal of duplicates, the final dataset comprises 36 peer-reviewed papers included in the analysis.

© IEOM Society International

3. Review Methodology

A comprehensive literature search was conducted across IEEE Xplore, ACM Digital Library, ScienceDirect (Elsevier), SpringerLink, MDPI, OnePetro, and arXiv. These sources collectively cover engineering education, human–computer interaction, energy systems, industrial training, and emerging immersive technologies. The search was guided by combinations of keywords spanning three dimensions: immersive technology, training and learning, and energy applications. Core keyword groups included terms related to extended reality (e.g., virtual reality, augmented reality, mixed reality, XR), training and learning (e.g., training, education, learning, simulation, operator training), and energy systems and applications (e.g., energy, power systems, nuclear, oil and gas, renewable energy, safety, maintenance). These terms were combined using Boolean operators to identify studies explicitly addressing immersive technologies for training-related purposes in energy domains. Reference lists of relevant review and survey papers were also examined to identify additional foundational or frequently cited studies.

3.1. Screening and Classification

Following the initial search, all identified records were screened using a set of predefined inclusion and exclusion criteria. Studies were included if they: (i) addressed the use of immersive technologies (VR, AR, or MR), (ii) focused on training or learning objectives, and (iii) were situated within an energy-related domain, including fossil energy systems, nuclear energy, or renewable energy systems. Both empirical studies and well-documented system designs or reviews were considered, provided they explicitly targeted training or learning outcomes. Studies were excluded if they focused solely on visualization, design, planning, or public communication without a training or educational component, or if they addressed immersive technologies in non-energy industrial domains without clear relevance to energy systems. Editorials, short abstracts without sufficient methodological detail, and non-scholarly sources were also excluded.

3.2. Data Extraction

For each included study, a structured set of attributes was extracted to support systematic comparison and synthesis. The extracted fields include bibliographic information (authors, year, and publication venue), immersive technology type (VR, AR, or MR), and detailed descriptions of the technology and system implementation where reported. Additional fields capture the pedagogical approach (e.g., experiential learning, procedural training, simulation-based rehearsal), application context (operator training, maintenance/field service, safety/emergency, education), energy domain, and intended training objectives. Where available, information on study participants, evaluation methods, and reported outcomes was also recorded.

4. Comparative Taxonomy of Immersive Learning in Energy

To synthesize over two decades of research spanning multiple energy domains, immersive technologies, and training objectives, this survey adopts a comparative taxonomy that organizes prior work along a small set of conceptually meaningful dimensions. Rather than enumerating individual studies in isolation, the taxonomy highlights recurring patterns, contrasts, and gaps across the literature, providing a structured lens through which diverse applications of IL in energy systems can be analyzed. The proposed taxonomy is defined by five key dimensions that collectively capture the pedagogical intent, technological choices, and evidentiary strength of IL applications in the energy sector.

The primary organizing dimension is the training priority, which reflects the dominant educational objective of each study. Studies are grouped into operator training, maintenance and field service, safety and emergency response, four core training priorities that emerged consistently across the literature: operator training, maintenance and field service, safety and emergency response, and workforce development. These categories correspond to distinct learner populations, task characteristics, and pedagogical needs. Operator training emphasizes system-level understanding and decision-making, maintenance and field service focus on procedural accuracy and task execution, and safety and emergency response target rare, high-consequence events that require rapid and coordinated action. Each study is situated within a specific energy domain, including fossil energy systems (e.g., oil and gas, refining, coal), nuclear energy, and renewable energy systems (e.g., wind, solar, hydropower). This dimension captures domain-specific constraints such as regulatory requirements, risk profiles, and operational complexity, which strongly influence both training design and technology adoption.

The proposed taxonomy is structured along three primary dimensions: training objective, energy domain, and XR modality. The training objective dimension distinguishes between operator training, maintenance/field service, safety/emergency response, and education/workforce development, reflecting the functional intent of immersive

© IEOM Society International

deployment rather than the technology alone. The energy domain dimension captures sector-specific contexts, including nuclear, grid/power systems, oil and gas, renewables (wind, solar, wave), and mining/coal, acknowledging that operational risk profiles, regulatory environments, and workforce structures differ substantially across domains. The XR modality dimension differentiates among simulators, VR, AR, MR, and CAVE systems, recognizing that each modality affords distinct levels of immersion, interaction fidelity, and spatial realism. Multiple studies that share these structural characteristics are grouped within the same row and cited collectively as citation clusters, emphasizing patterns of adoption rather than individual implementations.

Table 1. Unified taxonomy of IL applications for training in the energy sector (2000–2025), organized by XR modality, training priority, and energy domain.

Priority	Energy Domain	XR Modalities	Citations
Operator Training	Nuclear	VR/ Simulator /CAVE	Koskinen et al. (2021); Masiello et al. (2022); Bergroth et al. (2018); Jorge et al. (2010); Boring (2009); Li et al. (2023)
	Grid / Power	VR	Mondragón Bernal et al. (2022); Neto et al. (2023); Teodoro et al. (2023)
	Oil & Gas	Simulator/CAVE	Wilkinson & Corbett (2016)
Maintenance / Field Service	Nuclear	VR	Nash et al. (2018)
	Grid / Power	Simulator / VR	Chang et al. (2010)
	Oil & Gas	AR	Koteleva et al. (2020)
	Renewables – Wind	VR/Serious Game	Chen & Shieh (2023); Cheng et al. (2024)
Safety / Emergency	Nuclear	VR / MR	Arakawa et al. (2024); Pakarinen et al. (2024)
	Grid / Power	VR	Galvan et al. (2010)
	Renewables – Wind	VR	Li et al. (2022)
	Renewables – Solar/PV	VR / AR	Erten et al. (2022)
	Mining / Coal	VR / Serious Game	Grabowski & Jankowski (2015); Li et al. (2020); Gürer et al. (2023); Bellanca et al. (2019)
Education / Workforce Development	Nuclear	VR/AR	Popov et al. (2021)
	Grid / Power	VR	Barata et al. (2015); Borst et al. (2016)
	Renewables – Wind	VR	Abichandani et al. (2014); Frank et al. (2021)
	Renewables – Solar/PV	VR /AR	Abichandani et al. (2019); Karlina et al. (2024)
	Mining / Coal	VR + AR	Zhang et al. (2022)
Cross-Cutting / Reviews	Nuclear	VR	Pakarinen et al. (2024)
	Cross-domain	VR / AR/ MR / Simulator /CAVE	Kuhail et al. (2022); Huynh et al. (2016); Anifowose et al. (2023); Alhazzaa et al. (2025); Lucas et al. (2018); Pérez-Ramírez & Ontiveros-Hernández (2009)

As displayed in Table 1, nuclear energy exhibits the highest level of technological maturity and diversity, spanning traditional simulators, immersive VR, MR, and CAVE systems, primarily for operator training and safety applications. In contrast, grid and power systems rely predominantly on VR-based operator and substation training, with limited modality diversity. Oil and gas remain simulator-dominant for operator training, while AR is mainly used for maintenance support. In the renewable sector, adoption is largely education- and workforce-driven rather than operator-focused: wind energy emphasizes VR and serious games for maintenance and safety, solar incorporates both VR and AR for safety and instructional modules, and wave energy remains mostly non-immersive. Mining and coal applications are overwhelmingly safety-oriented, heavily utilizing VR and serious-game approaches for occupational health training. Across all domains, VR is the dominant modality, while AR adoption is selective and CAVE systems appear exclusively in nuclear contexts. Overall, the taxonomy suggests that immersive deployment maturity correlates with operational risk and regulatory intensity, with nuclear leading in breadth and depth, mining focusing on hazard mitigation, and renewables prioritizing workforce education over advanced operational immersion.

4.1 Operator Training

Operator training represents one of the earliest and most conservative applications of immersive technologies in the energy sector, particularly within nuclear and power grid domains. Across these systems, IL is primarily used to support rehearsal of complex procedures, exposure to abnormal operating conditions, and development of situational awareness in environments where real-world training is impractical or unsafe. In nuclear energy, operator training has focused on virtualized control rooms and plant environments that replicate instrumentation layouts, alarm systems, and operational workflows. These systems enable interaction with control interfaces and simulated plant states without disrupting live operations, supporting familiarization, skill refreshment, and rehearsal of abnormal scenarios (Boring, 2009; Jorge et al., 2010; Pakarinen & Laarni, 2024). A defining feature of this cluster is its emphasis on rare, high-consequence events, such as accident sequences and radiological incidents, that cannot be safely enacted in physical facilities. Simulation-based rehearsal allows repeated exposure to such scenarios, supporting procedural memory and coordinated decision-making under stress. However, operator training in nuclear systems is shaped by a conservative validation culture. Regulatory requirements and safety considerations impose high standards for acceptance, resulting in cautious adoption of immersive technologies. Consequently, many studies emphasize fidelity, alignment with existing simulator-based practices, and participatory design, while empirical evaluations often rely on small pilot studies or qualitative assessments. This conservatism promotes methodological rigor but limits the pace of innovation and breadth of reported evidence.

In power grid systems, immersive operator training has focused on substations, switching operations, and distributed control contexts. Virtual environments are used to represent substation layouts and system states, allowing operators to practice procedures and understand system behavior without exposure to high-voltage infrastructure (Chang et al., 2010; Mondragón-Bernal et al., 2022). Compared to nuclear applications, these systems place greater emphasis on procedural rehearsal and spatial understanding than on high-level diagnostic or strategic decision-making. Across energy domains, operator training remains dominated by simulation-based pedagogy. Immersive environments are primarily used to replicate real systems and procedures, enabling repeated practice under controlled conditions. While the potential benefits of IL for operator preparedness are widely recognized, objective performance transfer metrics remain limited, particularly outside the nuclear domain. This highlights the need for cross-domain evaluation frameworks capable of assessing skill transfer, decision quality, and long-term retention.

4.2 Maintenance and Field Service Training

Maintenance and field service training constitutes one of the most active and application-driven areas of IL in the energy sector. Unlike operator training, which emphasizes system-level understanding, maintenance-focused applications prioritize procedural accuracy, spatial awareness, and task execution in hazardous or hard-to-access environments. In power grid applications, IL has been widely explored for high-voltage maintenance, including live-line work and substation-related tasks. Virtual environments allow technicians to rehearse dangerous procedures without exposure to electrical hazards, supporting step-by-step practice and spatial understanding (Pérez-Ramírez & Ontiveros-Hernández, 2009; Galván et al., 2010). More recent immersive systems incorporate fault handling and emergency maintenance scenarios, reinforcing diagnostic and corrective actions under time pressure (Mondragón-Bernal et al., 2022). While feasibility and usability are well established, evaluations often remain limited to engagement metrics rather than direct measures of field performance or error reduction.

In offshore oil and gas, maintenance and field service training continues to rely heavily on high-fidelity simulators for drilling and equipment operations (Wilkinson & Corbett (2016) / Maersk Training, 2016). These systems support procedural rehearsal and emergency preparedness in complex offshore environments but remain largely simulator-centric rather than XR-driven. Renewable energy systems, particularly offshore wind, present distinct challenges related to working at height, confined spaces, and harsh environmental conditions. IL in this domain focuses on turbine maintenance, electrical and hydraulic systems, and safety procedures. VR-based simulators and serious games are commonly used to expose technicians to these high-risk environments without physical danger, supporting troubleshooting and procedural rehearsal (Chen & Shieh, 2023; Cheng et al., 2024). Despite growing interest, many studies remain exploratory, with limited reporting on long-term skill transfer or operational impact

4.3 Safety and Emergency Response Training

Safety and emergency response training emerges as the most mature and consistently explored application of IL across energy domains. XR technologies are well aligned with the pedagogical requirements of preparing personnel for rare, high-consequence events that cannot be safely or economically rehearsed in real environments. In power grid systems, immersive training has been widely applied to electrical accidents, substation faults, and live-line hazards. Virtual environments allow trainees to experience accident sequences and practice correct responses without exposure to electrical risk, emphasizing hazard recognition and procedural compliance (Pérez-Ramírez & Ontiveros-Hernández, 2009; Mondragón-Bernal et al., 2022). Nuclear energy exhibits a strong alignment between IL and safety training needs. VR-based simulations support training for radiological exposure, accident management, decommissioning, and evacuation scenarios, often built upon simulator-based traditions (Nash et al., 2018; Masiello et al., 2022).

More recently, mixed reality appeared in narrowly scoped applications, such as radiation protection and instrument-centered training, where physical devices are coupled with virtual hazard visualization (Arakawa et al., 2024). While these MR applications demonstrate technical feasibility, they remain task-specific rather than comprehensive safety training platforms. In offshore oil and gas, simulator-based training continues to dominate emergency response preparation, supporting fire, explosion, and evacuation drills without disrupting operations (Wilkinson & Corbett (2016) / Maersk Training, 2016). Across domains, safety and emergency response training is characterized by simulation-based and serious-game pedagogies, with VR serving as the primary modality for creating controlled yet realistic emergency scenarios. Despite its relative maturity, evidence of long-term safety impact remains limited. Most studies report improvements in engagement, perceived preparedness, or short-term learning gains, while longitudinal outcomes, such as incident reduction or sustained performance improvement, are rarely assessed. Addressing this gap represents a critical opportunity for advancing the effectiveness of IL in safety-critical energy systems.

4.4 Education and Workforce Development

Education and workforce development represent a complementary but conceptually distinct application of IL in the energy sector. Unlike operator, maintenance, and safety training, which are typically oriented toward certified personnel and operational readiness, education-focused applications target students, early-career technicians, and prospective workforce entrants. The primary objective in this cluster is conceptual understanding, skills exposure, and career pathway development rather than immediate operational competence. IL in this category is commonly used to visualize abstract energy concepts, system behaviors, and spatial relationships that are difficult to convey through traditional instruction. In marine and renewable energy education, VR environments and interactive demonstrations have been used to illustrate energy conversion processes, system components, and operational principles, enabling learners to explore complex systems in an intuitive and engaging manner (Huynh et al., 2016). Similarly, immersive tools have been applied to building energy and solar contexts to support understanding of energy flows, system interactions, and simulation outcomes, often as a supplement to computational or classroom-based instruction (Erten et al., 2022; Alhazzaa et al., 2025).

Pedagogically, education-oriented immersive applications tend to emphasize experiential learning, exploration, and scaffolding rather than strict procedural fidelity. Serious games, guided virtual walkthroughs, and interactive simulations are frequently employed to support inquiry-based learning and conceptual reasoning. Evaluations in this cluster typically focus on learner engagement, perceived understanding, and attitudinal outcomes, with fewer studies assessing long-term knowledge retention or transfer to professional practice. Compared to other priority areas, education and workforce development exhibit greater flexibility in technology adoption and lower regulatory constraints. This has enabled broader experimentation with VR and AR, including early-stage comparative studies of immersive modalities. At the same time, the lack of standardized learning objectives and assessment frameworks limits cross-study comparability and makes it difficult to quantify the contribution of IL to workforce readiness. As energy systems evolve and demand new skill sets, this cluster represents an opportunity to bridge conceptual education and applied training through structured integration of IL with formal curricula and industry-aligned competencies.

5. Cross-Cutting Analysis and Research Gaps

The review synthesizes the landscape of IL research and applications in the energy sector through complementary views that jointly reveal temporal evolution, structural coupling, and distributional imbalance. Figure 2-a illustrates the temporal trend of publications (2000–2025) by training objective, showing a sharp increase after 2016, with nearly 70% of the reviewed studies published between 2021 and 2025. This growth is driven primarily by education/workforce applications, which account for approximately 47% of the total sample, followed by safety/emergency training at about 25%. Operator training represents roughly 22%, while maintenance/field service constitutes the smallest share at about 11%, reflecting comparatively modest and fluctuating growth. Figure 2-b highlights the cross-cutting role of VR, which dominates the modality landscape at approximately 64% of all studies. When simulators and serious-game systems are combined, they account for about 31%, largely concentrated in safety-critical and operator-focused contexts. AR-based systems represent roughly 11%, appearing selectively in maintenance and workforce training, while MR (≈3%) and CAVE systems (≈3%) remain marginal, underscoring the

© IEOM Society International

limited penetration of tightly coupled physical–virtual and large-scale immersive environments in energy training. Figure 2c–f quantifies distributions across key dimensions. Training priorities confirm the predominance of education/workforce applications (≈47%), followed by safety/emergency (≈25%) and operator training (≈22%). Modality distribution further reinforces VR's dominance (≈64%), with all other modalities representing substantially smaller shares. Energy domain distribution indicates that renewables lead with approximately 36% of publications, followed by nuclear at about 28%, grid/power at 22%, mining/coal at 14%, and oil/gas at 6%. Finally, hardware platforms reveal that HMD-based systems account for roughly two-thirds of deployments, far exceeding desktop-based systems, AR devices, industrial simulators, or CAVE installations.

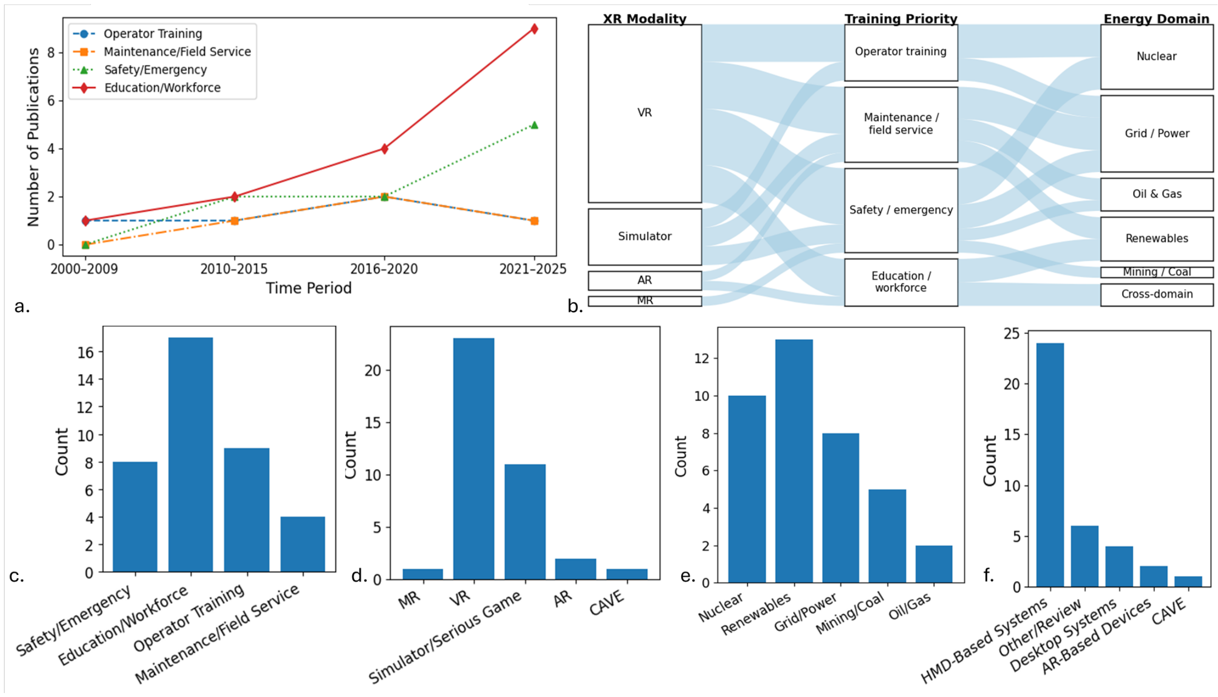

Figure 2. Cross-cutting analysis of IL for training in the energy sector (2000–2025), showing (a) temporal trends by training priority, (b) distribution of studies across XR modality, training priority, and energy domain, and (c–f) aggregate distributions by training priority, XR modality, energy domain, and hardware platforms.

5.1 Pedagogy vs. Technology

Across energy domains, technological innovation has consistently outpaced pedagogical development. Advances in graphics, interaction, head-mounted displays, and mobile platforms have enabled increasingly realistic and immersive training environments. However, many studies emphasize system capabilities and visual fidelity while providing limited discussion of instructional design principles, learning objectives, or assessment strategies. Simulation-based training dominates literature, often implicitly rather than explicitly grounded in learning theory. While experiential learning, procedural rehearsal, and serious-game approaches are frequently invoked, these pedagogical concepts are not always systematically operationalized or evaluated. As a result, similar immersive technologies are used across markedly different training contexts without clear justification for their pedagogical alignment. This gap suggests a need for stronger integration of learning science frameworks, such as experiential learning cycles, cognitive load theory, and mastery learning, into the design of immersive training systems for energy applications.

5.2 Evaluation Gaps

A pervasive challenge concerns evaluation rigor and consistency. Many studies across all three training priorities rely on small participant samples, often due to the practical constraints of working with specialized operators, technicians, or safety personnel. While such constraints are understandable in energy contexts, they limit statistical power and generalizability. More critically, objective transfer-to-field metrics are rarely reported. Evaluations frequently focus on usability, user satisfaction, or perceived realism rather than measurable improvements in task performance, error reduction, decision quality, or safety outcomes in real operational settings. Longitudinal assessments of retention and real-world impact are particularly scarce. In addition, the use of control groups or comparative baselines is uncommon.

Few studies directly compare immersive training with conventional methods such as classroom instruction, manuals, or traditional simulators. Without such comparisons, it remains difficult to attribute observed benefits specifically to IL rather than to novelty effects or increased training attention.

5.3 Domain Conservatism

The review also reveals clear differences in adoption pace and validation culture across energy domains. Nuclear energy exhibits the most conservative approach, characterized by rigorous safety requirements, regulatory oversight, and strong alignment with existing simulator-based training practices. As a result, immersive technologies are introduced cautiously, often through pilot studies and participatory design, with an emphasis on fidelity and procedural accuracy. In contrast, offshore wind and other renewable energy sectors demonstrate faster experimentation and innovation, driven by rapidly expanding workforces, evolving infrastructure, and fewer regulatory constraints on training methods. IL in these domains often adopts serious games and VR-based simulations with comparatively limited validation. The oil and gas sector occupies an intermediate position, balancing high-risk operational environments with commercial pressures and practical deployment considerations. Here, IL, particularly AR for field service, has seen increasing real-world use, but systematic evaluation remains limited. These domain-specific differences underscore the importance of contextualizing IL within regulatory, cultural, and operational constraints.

5.4 Scalability and Cost

Finally, scalability and cost present persistent challenges for widespread adoption of IL in energy training. While hardware costs for VR and AR devices have decreased over time, organizations must still account for expenses related to system integration, content development, and maintenance. High-fidelity simulations and scenario-rich environments require substantial upfront investment and ongoing updates to remain aligned with evolving equipment, procedures, and regulations. Instructor training and organizational readiness further complicate scalability. Effective deployment of IL often requires trainers who are comfortable with both the technology and the underlying pedagogical approach, as well as institutional support for integrating immersive tools into existing training curricula. Without sustainable strategies for content updates, instructor preparation, and technical support, IL initiatives risk remaining isolated pilots rather than becoming integral components of training programs.

6. Future Research Directions

6.1 Evidence-Based Evaluation Frameworks

A central priority for future research is the development of evidence-based evaluation frameworks tailored to IL in safety-critical energy contexts. Existing studies frequently rely on usability and acceptance metrics, which, while valuable, provide limited insight into actual learning effectiveness or operational impact. Future work should emphasize objective performance measures, such as task completion time, error rates, decision quality, and procedural compliance, and assess how these metrics translate from virtual environments to real-world settings. Longitudinal studies are particularly needed to evaluate skill retention and transfer, especially for high-risk, low-frequency events where training benefits may only manifest over extended periods. Comparative studies that include control groups or baseline training methods (e.g., classroom instruction, manuals, or conventional simulators) would further strengthen causal claims. Developing standardized evaluation protocols that can be adapted across energy domains would facilitate cross-study comparison and accelerate evidence accumulation.

6.2 Integration with Digital Twins

The integration of IL with digital twins represents a promising avenue for enhancing realism, adaptability, and relevance in energy training. Digital twins, as dynamic, data-driven representations of physical systems, can provide real-time or scenario-based inputs to immersive environments, enabling training experiences that reflect current system states, historical incidents, or projected future conditions. For operator training, coupling VR control rooms with digital twins can support realistic rehearsal of system behavior under varying loads, faults, or environmental conditions. For maintenance and field service, digital twins can inform AR-based guidance with up-to-date asset information and predictive maintenance insights. Further research is needed to explore such architectures, data integration strategies, and pedagogical models that effectively leverage digital twins without overwhelming learners or introducing unnecessary complexity.

6.3 Adaptive and Personalized Training

Another important research direction involves adaptive and personalized immersive training. Most existing systems deliver static scenarios or fixed procedural sequences, regardless of learner expertise, performance, or learning

© IEOM Society International

progress. Advances in learning analytics, artificial intelligence, and user modeling offer opportunities to tailor immersive experiences to individual learners. Adaptive training systems could adjust scenario difficulty, feedback frequency, or task sequencing based on observed performance, enabling more efficient learning and targeted skill development. Personalization is particularly relevant in energy contexts where trainee backgrounds vary widely, ranging from novices to experienced operators. Future studies should investigate how adaptive mechanisms influence learning outcomes, cognitive load, and user trust, as well as how personalization can be implemented responsibly in safety-critical training environments.

6.4 Certification and Regulatory Acceptance

The certification and regulatory acceptance of IL remain a key challenge, especially in highly regulated domains such as nuclear energy and power grid operations. While immersive technologies offer clear pedagogical benefits, their integration into formal training and certification pathways requires alignment with regulatory standards, validation criteria, and auditing practices. Future research should explore frameworks for certifying immersive content, documenting learning outcomes, and demonstrating equivalence or complementarity with existing training methods. Collaboration among researchers, industry practitioners, and regulatory bodies will be essential to establish trust and define acceptable evidence thresholds. Addressing these institutional dimensions is critical for transitioning IL from supplemental training tools to formal components of energy workforce development

7. Conclusion

This survey reviewed two decades of research on IL for training in energy systems (2000–2025), focusing on operator training, maintenance and field service, safety and emergency response, four core training priorities that emerged consistently across the literature: operator training, maintenance and field service, safety and emergency response, and workforce development. From a pedagogical perspective, immersive technologies address training challenges that are distinctive to energy systems, including high-risk, low-frequency events and operational contexts that are unsafe or impractical to reproduce in real environments. By introducing a cross-domain comparative taxonomy, this work synthesizes a fragmented literature spanning nuclear, power grid, oil and gas, and renewable energy sectors. The analysis shows clear alignment between immersive modalities and training priorities: VR is predominantly used for simulation and emergency rehearsal, AR increasingly supports in-situ maintenance and field service, and experiential approaches are most common in safety-critical training. MR represents a newer class of immersive technology, and its limited presence in the reviewed literature reflects both its relative maturity and the conservative adoption patterns typical of safety-critical energy domains.

Acknowledgement

This research was sponsored by the Ocean Energy Safety Institute Consortium (OESIC) through a grant from the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement (BSEE), and the U.S. Department of Energy (DOE) and was accomplished under Agreement Number E21AC00000. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government.

References

Abichandani, P., Fligor, W., and Fromm, E., A cloud enabled virtual reality based pedagogical ecosystem for wind energy education, *Proceedings of the 2014 IEEE Frontiers in Education Conference (FIE)*, pp. 1-7, 2014.

Abichandani, P., Mcintyre, W., Fligor, W., and Lobo, D., Solar energy education through a cloud-based desktop virtual reality system, *IEEE Access*, vol. 7, pp. 147081-147093, 2019.

Alhazzaa, A., Kim, J., and Park, J., Immersive technologies in education: Exploring user experience and learning outcomes of VR and AR for building energy simulations, *Energy and Buildings*, vol. 301, p. 113779, 2025.

Anifowose, H., Alhazzaa, K., and Dixit, M., ENERGYSIM: techniques for advancing building energy education through immersive virtual reality (VR) simulation, *Journal of Information Technology in Construction*, vol. 28, 2023.

Arakawa, H., Fujibuchi, T., Kaneko, K., Okada, Y., and Tomisawa, T., Radiation-training system with a custom survey-meter mock-up in a browser-based mixed reality environment, *Nuclear Engineering and Technology*, vol. 56, no. 6, pp. 2428-2435, 2024.

Barata, P. N. A., Ribeiro Filho, M., and Nunes, M. V. A., Consolidating learning in power systems: Virtual reality applied to the study of the operation of electric power transformers, *IEEE Transactions on Education*, vol. 58, no. 4, pp. 255-261, 2015.

Bellanca, J. L., Orr, T. J., Helfrich, W. J., and Eiter, B. M., Developing a virtual reality environment for mining research, *Mining Engineering*, vol. 71, no. 9, pp. 50–56, 2019.

Bergroth, J. D., Koskinen, H. M., and Laarni, J. O., Use of immersive 3-D virtual reality environments in control room validations, *Nuclear Technology*, vol. 202, no. 2-3, pp. 278-289, 2018.

Boring, R. L., Using nuclear power plant training simulators for operator performance and human reliability research, *Proceedings of the American Nuclear Society Topical Meeting on Human Performance*, American Nuclear Society, 2009.

Borst, C. W., Ritter, K. A., and Chambers, T. L., Virtual energy center for teaching alternative energy technologies, *Proceedings of 2016 IEEE Virtual Reality (VR)*, pp. 157-158, 2016.

Chang, Y.-C., Fang, T.-Y., Zhang, Y., and Hu, J., A training simulation system for substation equipment maintenance, *Proceedings of the IEEE International Conference on Multimedia and Virtual Reality in Human–Computer Interaction*, 2010.

Chen, Y.-S., and Shieh, M.-D., Serious game design for high-risk training: The case of offshore wind turbine maintenance personnel training, *Lecture Notes in Computer Science: HCI in Games*, Springer, pp. 225–238, 2023.

Cheng, C.-H., Lin, Y.-C., and Huang, C.-Y., Virtual reality serious game design for offshore wind turbine basic technical training: Electrical and hydraulics modules, *International Journal of Human–Computer Interaction*, Advance online publication, 2024.

Erten, B., Oral, B., and Yakut, M. Z., The role of virtual and augmented reality in occupational health and safety training of employees in PV power systems and evaluation with a sustainability perspective, *Journal of Cleaner Production*, vol. 379, p. 134499, 2022.

Frank, K., Gardner, A. E., Ciobanescu Husanu, I. N., Chiou, R. Y., and Ruane, R., Green stem: Virtual reality renewable energy laboratory for remote learning, *ASME International Mechanical Engineering Congress and Exposition*, vol. 85659, p. V009T09A018, American Society of Mechanical Engineers, 2021.

Galvan, I., Ayala, A., Muñoz, J., Salgado, M., Rodríguez, E., and Pérez, M., Virtual reality system for training of operators of power live lines, *Proceedings of the World Congress on Engineering and Computer Science*, vol. 1, pp. 20-22, 2010.

Grabowski, A., and Jankowski, J., Virtual reality-based pilot training for underground coal miners, *Safety Science*, vol. 72, pp. 310-314, 2015.

Gürer, S., Surer, E., and Erkayaoğlu, M., MINING-VIRTUAL: A comprehensive virtual reality-based serious game for occupational health and safety training in underground mines, *Safety Science*, vol. 166, p. 106226, 2023.

Huynh, T., Hou, G., and Wang, J., Communicating Wave Energy: An Active Learning Experience for Students, *American Journal of Engineering Education*, vol. 7, no. 1, pp. 37-46, 2016.

Jorge, J., Lima, F., Lima Netto, J., and Resende, J., Human–system interface based on speech recognition: Application to a virtual nuclear power plant control desk, *Progress in Nuclear Energy*, vol. 52, no. 4, pp. 379–386, 2010.

Karlina, M., Chandra, A. N., Imamora, M., and Idrus, H., Development of Renewable Energy Modules with Contextual Teaching Learning Helpful Augmented Reality (AR) Integrated Al-Qur'an Class X SMA/MA, *Impulse: Journal of Research and Innovation in Physics Education*, vol. 4, no. 1, pp. 1-11, 2024.

Koskinen, H., Laarni, J., Liinasuo, M., Salonen, T., Pakarinen, S., Lukander, K., and Passi, T., Augmenting Field Operator Training Through Virtual Reality, pp. 79-88, 2021. https://doi.org/10.13182/T124-34327

Koteleva, N., Buslaev, G., Valnev, V., and Kunshin, A., Augmented reality system and maintenance of oil pumps, *International Journal of Engineering*, vol. 33, no. 8, pp. 1620-1628, 2020.

Kuhail, M. A., ElSayary, A., Farooq, S., and Alghamdi, A., Exploring immersive learning experiences: A survey, *Informatics*, vol. 9, no. 4, p. 75, MDPI, 2022.

Li, J. Y., Du, J. L., Gu, L., Zhang, Y. P., Sheng, X., Lin, C., and Wang, Y., The development of training platform for CiADS using cave automatic virtual environment, *Nuclear Engineering and Technology*, vol. 55, no. 7, pp. 2656-2661, 2023.

Li, M., Sun, Z., Jiang, Z., Tan, Z., and Chen, J., A virtual reality platform for safety training in coal mines with AI and cloud computing, *Discrete Dynamics in Nature and Society*, vol. 2020, no. 1, p. 6243085, 2020.

Li, W., Esmaeili, B., and Yu, L. F., Simulating wind tower construction process for virtual construction safety training and active learning, *Proceedings of 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 369-372, 2022.

Lucas, H., Pinnington, S., and Cabeza, L. F., Education and training gaps in the renewable energy sector, *Solar Energy*, vol. 173, pp. 449-455, 2018.

Masiello, I., Kallio, S., and Laarni, J., Simulation-based virtual reality training for the nuclear sector: A pilot study, *Sustainability*, vol. 14, no. 13, p. 7984, 2022.

Masoud, S., Zhu, M., Rickli, J., and Djuric, A., Challenges and future directions for extended reality-enabled robotics laboratories during COVID-19, *Technology Interface International Journal*, vol. 23, no. 1, pp. 1-22, 2022.

Masoud, S., Tutuncuoglu, G., Jahanmahin, R., and Alinezha, E., Using 360° Virtual Reality to Enhance Learning and Engagement in Semiconductor Training, *Proceedings of 2025 IEEE 68th International Midwest Symposium on Circuits and Systems (MWSCAS)*, pp. 1109-1113, 2025.

Mondragón Bernal, I. F., Lozano-Ramírez, N. E., Puerto Cortes, J. M., Valdivia, S., Muñoz, R., Aragón, J., and Hernández, G., An immersive virtual reality training game for power substations evaluated in terms of usability and engagement, *Applied Sciences*, vol. 12, no. 2, p. 711, 2022.

Nash, B., Walker, A., and Chambers, T., A simulator based on virtual reality to dismantle a research reactor assembly using master-slave manipulators, *Annals of Nuclear Energy*, vol. 120, pp. 1-7, 2018.

Neto, J., Lima, F., et al., Enhancing electrical substation training through multi-user virtual reality techniques, *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, ACM, 2023.

Pakarinen, S., Laarni, J., Koskinen, H., Passi, T., Liinasuo, M., and Salonen, T. T., Virtual-Reality training solutions for nuclear power plant field operators: A scoping review, *Progress in Nuclear Energy*, vol. 169, p. 105104, 2024.

Pérez-Ramírez, M., and Ontiveros-Hernández, N. J., Virtual reality as a comprehensive training tool, *WILE-MICAI*, Guanajuato, Mexico, 2009.

Popov, O. O., Iatsyshyn, A. V., Iatsyshyn, A. V., Kovach, V. O., Artemchuk, V. O., Gurieiev, V., and Kiv, A. E., Immersive technology for training and professional development of nuclear power plants personnel, *Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021)*, vol. 2898, pp. 230-254, 2021.

Skarbez, R., Smith, M., and Whitton, M. C., Revisiting Milgram and Kishino's reality-virtuality continuum, *Frontiers in Virtual Reality*, vol. 2, p. 647997, 2021.

Teodoro, P., Mattioli, L., Cyrino, G., Cardoso, A., Lamounier, E., Zorcot, E., and Ramos, D., Training routine for electrical power station operators using virtual reality, *Perspectives and Trends in Education and Technology: Selected Papers from ICITED 2022*, Springer Nature Singapore, pp. 387-398, 2023.

Wilkinson, J., and Corbett, E., The use and uptake of simulators for training offshore drilling crews, *Hazards 26: Process Safety and Environmental Protection Conference*, Institution of Chemical Engineers (IChemE), 2016.

Zhang, C., Wang, X., Fang, S., and Shi, X., Construction and application of VR-AR teaching system in coal-based energy education, *Sustainability*, vol. 14, no. 23, p. 16033, 2022.

Biographies

Nadia Anjum is a graduate researcher in the Department of Industrial and Systems Engineering at Wayne State University, working under the supervision of Dr. Sara Masoud in the Smart Immersive Modeling (SIM) Lab. Her research focuses on the integration of data analytics, immersive technologies, and human-centered engineering to address real-world challenges in energy, transportation, and smart infrastructure systems. She applies data-driven modeling and emerging tools such as virtual and augmented reality to support training, and decision-making.

Dr. Sara Masoud is an Assistant Professor of Industrial and Systems Engineering at Wayne State University whose research centers on human-centered engineering, immersive technologies, and data-driven modeling of complex energy and infrastructure systems. She integrates advanced analytics, simulation, and virtual, augmented, and mixed reality environments to enhance operator training, workforce development, and system resilience in high-risk domains. Her work examines how human cognition, trust, and decision-making affect system performance under both normal and abnormal conditions. Dr. Masoud leads multidisciplinary projects across energy, manufacturing, and smart agriculture, producing methodological frameworks that connect research with real-world deployment.

Dr. Murat Yildirim, Associate Professor of Industrial and Systems Engineering at Wayne State University, specializes in reliability engineering, maintenance optimization, and data-driven decision support for energy and industrial systems. His research addresses degradation modeling, predictive and condition-based maintenance, lifecycle cost analysis, and risk-informed decision-making under uncertainty. By combining stochastic modeling with practical applications, he advances methodologies that enhance asset health monitoring, system availability, and resilience in critical energy infrastructure. He maintains strong collaborations across academia and industry and actively mentors students in reliability and operations research.

Dr. Feng Qiu is a senior scientist and group leader at Argonne National Laboratory, focusing on optimization and large-scale energy system modeling. His research develops advanced mathematical and computational methods to improve power grid planning, operations, renewable integration, and resilience under uncertainty. With expertise in mixed-integer and stochastic optimization and scalable algorithms, Dr. Qiu translates theoretical advances into decision-support tools used by government agencies and utilities. His work supports national priorities in grid reliability, flexibility, and decarbonization while strengthening the efficiency and resilience of modern energy systems.

© IEOM Society International