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Integrated Change Management and Digital Transformation Framework for Accelerating Enterprise-Wide Adoption of Sustainable Energy Technologies in Large Organizations

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Abstract: Large organizations are increasingly adopting renewable energy, energy-efficiency systems, energy storage, electrification, smart metering, and digital energy-management technologies. However, enterprise-wide implementation is often constrained by fragmented governance, legacy systems, inadequate digital infrastructure, workforce limitations, organizational resistance, and weak alignment between sustainability goals and operational priorities. This study developed an Integrated Change Management and Digital Transformation Framework to support coordinated adoption and scaling of sustainable energy technologies across large organizations. The framework integrates six iterative phases: organizational diagnosis, strategic alignment, collaborative solution design, pilot implementation, enterprise scaling, and institutionalization with continuous optimization. These phases are supported by governance, stakeholder engagement, workforce development, digital energy architecture, technology prioritization, risk and readiness assessment, performance measurement, and benefits realization. The findings show that sustainable energy adoption should be treated as an enterprise-wide socio-technical transformation rather than as a stand-alone technology deployment. Effective implementation requires the coordinated management of organizational readiness, leadership, workforce capability, digital integration, stakeholder participation, regulatory requirements, and performance monitoring. The framework therefore provides a structured basis for selecting technologies, assessing readiness, managing implementation risks, scaling successful initiatives, and monitoring operational, financial, energy, and environmental outcomes. It also supports continuous adaptation as organizational conditions, technology maturity, resource availability, and regulatory requirements change.

Keywords: *Change Management; Digital Transformation; Sustainable Energy Technologies; Enterprise Adoption; Energy Management; Organizational Readiness; Socio-Technical Systems.*

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I. INTRODUCTION

➢ *Background of the Study*

The transition toward low-carbon and resource-efficient energy systems has become a strategic requirement for governments, industries, and large organizations. Climate-change mitigation pathways require substantial reductions in greenhouse gas emissions through energy efficiency, electrification, renewable energy deployment, demand-side management, and the replacement of carbon-intensive technologies [1]. At the same time, energy security concerns, volatile energy prices, regulatory obligations, investor expectations, and corporate net-zero commitments are increasing pressure on organizations to transform how energy is generated, purchased, distributed, monitored, and consumed [2].

Sustainable energy technologies include renewable electricity generation, battery energy storage systems, industrial electrification, waste-heat recovery, high-efficiency motors and drives, low-carbon heating and cooling, smart buildings, microgrids, electric-vehicle infrastructure, energy-efficient process equipment, and digitally enabled energy-management systems. Accelerating their adoption is necessary to translate corporate sustainability commitments into measurable operational performance. However, the availability and technical maturity of these technologies do not automatically produce successful enterprise-wide

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adoption. Implementation outcomes depend on organizational capabilities, investment governance, infrastructure compatibility, user acceptance, regulatory conditions, and the organization's capacity to manage technological and behavioral change.

The International Energy Agency identifies renewable energy, energy efficiency, electrification, and digitalized energy systems as mutually reinforcing components of the energy transition [2], [3]. Within organizations, the International Organization for Standardization's ISO 50001:2018 provides a systematic basis for establishing, implementing, maintaining, and improving an Energy Management System (EnMS). It requires organizations to integrate energy performance into strategic and operational processes, establish energy baselines, define Energy Performance Indicators (EnPIs), and demonstrate continual improvement [4]. Although this management-system approach strengthens accountability, it does not independently resolve the organizational, behavioral, and digital-integration challenges associated with scaling diverse energy technologies across multiple facilities and business functions.

Digital transformation can provide the technical foundation for more coordinated sustainable-energy adoption. Technologies such as the Internet of Things (IoT), smart sensors, cloud and edge computing, digital twins, advanced metering infrastructure, artificial intelligence, machine learning, data analytics, blockchain, and automated control systems can improve energy visibility, forecasting, asset optimization, predictive maintenance, demand flexibility, and performance verification [5], [6]. For example, IoT-enabled monitoring can connect dispersed energy assets and collect time-stamped operational data, while analytics can identify consumption anomalies, predict equipment degradation, optimize energy schedules, and support investment decisions. Digital platforms can also provide a common information architecture through which corporate energy targets are translated into site-level actions and verified performance outcomes.

Nevertheless, installing digital technologies does not, by itself, constitute digital transformation. Digital transformation involves significant changes in organizational processes, value creation, structures, capabilities, decision rights, and stakeholder relationships enabled by combinations of digital technologies [7]. It therefore extends beyond equipment automation or the conversion of analogue records into digital formats. Studies of organizational digital transformation consistently show that its outcomes are shaped by strategic alignment, leadership, organizational structure, workforce capability, culture, data governance, and the capacity to continuously reconfigure organizational resources [7–9].

The relationship between digital transformation and sustainability is particularly important because digital technologies can both enable and constrain environmental performance. Digital systems can improve resource efficiency, traceability, operational coordination, and evidence-based decision-making. Conversely, poorly governed digitalization can increase electricity demand, cybersecurity exposure, data fragmentation, technology dependence, and electronic waste. Digital transformation must therefore be deliberately aligned with sustainability objectives rather than treated as intrinsically sustainable [10]. Sustainable-energy adoption requires a digital architecture that provides measurable environmental and operational value without creating disproportionate technological, financial, or governance burdens.

Large organizations face distinctive adoption challenges. Their operations may span multiple geographical locations, regulatory jurisdictions, business units, technical standards, asset classes, and workforce groups. Energy investment decisions may be distributed among corporate sustainability, engineering, operations, finance, procurement, information technology, cybersecurity, facilities management, and executive leadership functions. These groups frequently use different performance criteria, planning horizons, data systems, and risk tolerances. A technology that is financially attractive at one facility may be technically incompatible, operationally disruptive, or institutionally unacceptable at another.

Empirical research on sustainable-energy technology adoption among large organizations has identified barriers associated with capital availability, information quality, internal decision processes, policy uncertainty, split incentives, procurement requirements, and organizational priorities [11]. The challenge is therefore not limited to selecting technically suitable equipment. It involves coordinating strategic intent, investment decisions, infrastructure preparation, employee behavior, governance arrangements, data flows, performance measurement, and continuous improvement across the enterprise.

This challenge has a socio-technical character. Socio-technical transition theory explains that major technological transformations require coordinated changes in technologies, infrastructure, user practices, regulation, organizational networks, and cultural meanings [12]. Within an enterprise, sustainable-energy adoption similarly changes work processes, responsibilities, competencies, performance expectations, and relationships among organizational functions. Employees may be required to operate unfamiliar equipment, use new digital interfaces, share previously isolated data, accept automated decision support, or modify established production routines. Accordingly, adoption cannot be managed solely as an engineering project.

Organizational readiness is central to this process. Readiness for change reflects both the shared commitment of organizational members to implement a proposed change and their collective confidence in their ability to perform the required tasks [13]. These conditions are influenced by perceived value, leadership support, resource availability, task demands, prior experience, and implementation capability. At the user level, the Unified Theory of Acceptance and Use of Technology (UTAUT) demonstrates that technology use is affected by performance expectancy,

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effort expectancy, social influence, and facilitating conditions [14]. These factors are directly relevant to digitally enabled sustainable-energy systems because employees must perceive the systems as useful, usable, organizationally supported, and compatible with their working environment.

Change-management research further indicates that sustainable organizational transformation requires a credible change rationale, stakeholder participation, leadership alignment, effective communication, capability development, implementation support, progress monitoring, and institutional reinforcement [15]. These requirements must be connected to the technical stages of energy-technology selection, digital integration, pilot testing, deployment, measurement, and optimization. Treating change management and digital implementation as separate workstreams risks producing technically functional systems that are weakly adopted or well-communicated initiatives that lack reliable technical and data foundations.

This study therefore proposes an Integrated Change Management and Digital Transformation Framework for accelerating enterprise-wide adoption of sustainable energy technologies in large organizations. The framework positions adoption as a continuous socio-technical transformation process that integrates strategy, governance, people, process, technology, data, risk, and performance management.

➢ *Problem Statement*

Large organizations are under increasing pressure to reduce energy costs, improve energy security, meet emissions-reduction commitments, and comply with environmental and energy-related requirements. Although sustainable energy technologies are increasingly available, many organizations encounter difficulty moving from isolated demonstrations and facility-level pilots to coordinated enterprise-wide adoption.

The central problem is not necessarily a shortage of sustainable-energy solutions. Rather, it is the absence of an integrated organizational mechanism for aligning technology selection, digital infrastructure, investment governance, operational requirements, workforce adoption, and performance measurement. Sustainable-energy projects are commonly implemented as separate capital projects, information-technology deployments, engineering modifications, or sustainability initiatives. This fragmented approach can produce incompatible data architectures, duplicated investments, inconsistent performance indicators, unclear ownership, and weak transfer of lessons between facilities.

Several related implementation problems emerge from this fragmentation. First, technology decisions may be based primarily on expected energy savings or financial return without adequately considering operational readiness, cybersecurity, workforce capability, infrastructure compatibility, scalability, and regulatory exposure. Second, pilot projects may demonstrate technical feasibility but fail to scale because the processes, governance arrangements, and competencies required for replication have not been institutionalized. Third, digital platforms may generate large volumes of energy data without establishing data ownership, quality requirements, interoperability standards, decision rules, or accountability for corrective action. Fourth, employees may resist new systems when their operational value, role implications, or required competencies are not clearly addressed.

Existing knowledge remains distributed across several research and practice domains. Energy-management standards provide systematic requirements for improving energy performance [4], but they offer limited detail on managing digital transformation and workforce adoption. Digital-transformation frameworks examine strategy, technology, organizational capabilities, and business-model change [7–9], but they do not always address the engineering, measurement, and operational requirements of sustainable-energy systems. Change-management models emphasize leadership, communication, participation, and reinforcement [13], [15], but generally provide limited guidance for technology-portfolio evaluation, data architecture, energy-performance verification, and cross-facility scaling. Sustainability-transition research explains broader socio-technical change [12], but its system-level orientation requires adaptation for enterprise implementation.

The absence of integration among these domains creates a practical and theoretical gap. Large organizations require a framework that can:

- Assess technical, digital, organizational, financial, and regulatory readiness;
- Align sustainable-energy investments with corporate strategy and operational priorities;
- Prioritize technologies using transparent and multidimensional criteria;
- Establish interoperable digital-energy data systems;
- Prepare and support affected stakeholders;
- Convert successful pilots into repeatable enterprise deployment models;
- Verify energy, environmental, financial, and operational benefits; and
- Institutionalize continuous learning and performance improvement.

Without such integration, organizations may invest in technically appropriate technologies while failing to achieve sustained adoption, enterprise scalability, or measurable benefits. This study addresses the gap by developing a unified framework that connects change-management mechanisms with digital-transformation capabilities and sustainable-energy implementation requirements.

➢ *Aim of the Study*

The aim of this study is to develop an Integrated Change Management and Digital Transformation Framework for accelerating the enterprise-wide adoption, scaling, and institutionalization of sustainable energy technologies in large organizations.

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The framework is intended to provide a structured mechanism for coordinating strategic alignment, technology prioritization, organizational readiness, stakeholder engagement, digital-energy architecture, implementation governance, workforce capability development, risk management, and performance measurement.

➢ *Research Objectives*

The specific objectives of the study are to:

- Examine the strategic, technological, organizational, behavioral, financial, operational, and regulatory factors affecting the adoption of sustainable energy technologies in large organizations;
- Evaluate relevant concepts and theories from organizational change management, digital transformation, technology acceptance, dynamic capabilities, energy management, and socio-technical transition research;
- Identify the limitations of existing change-management, digital-transformation, and sustainable-energy implementation frameworks when applied independently;
- Develop an integrated framework that connects organizational change processes with digital and sustainable-energy implementation activities;
- Establish a multidimensional mechanism for assessing organizational readiness, digital maturity, implementation risk, and technology scalability;
- Define an enterprise digital-energy architecture for data acquisition, integration, analytics, decision support, cybersecurity, and performance reporting;
- Develop a phased implementation pathway for diagnosing current conditions, aligning strategy, co-designing solutions, piloting technologies, scaling deployment, and institutionalizing continuous improvement; and
- Specify a validation and performance-measurement protocol for evaluating the framework using expert assessment, organizational case studies, and longitudinal implementation data.

➢ *Research Questions*

The study is guided by the following research questions:

- What strategic, technological, organizational, behavioral, financial, operational, and regulatory factors influence sustainable-energy technology adoption in large organizations?
- How can change-management principles and digital-transformation capabilities be integrated to support enterprise-wide sustainable-energy adoption?
- What limitations arise when existing energy-management, change-management, and digital-transformation frameworks are applied separately?
- What framework components are required to align sustainable-energy technology selection with organizational strategy, operational readiness, workforce capability, and digital infrastructure?
- How should large organizations assess adoption readiness, digital maturity, implementation risk, and enterprise scalability?
- What digital-energy architecture is required to support interoperable data collection, analytics, cybersecurity, decision-making, and performance verification?
- What implementation stages and governance arrangements can support the transition from isolated pilot projects to sustained enterprise-wide adoption?
- How can the validity, usability, and implementation effectiveness of the proposed framework be evaluated?

➢ *Significance and Contributions*

The study is significant because it addresses the organizational difficulty of converting sustainable-energy ambitions into coordinated, scalable, and measurable enterprise action. Its contributions are theoretical, methodological, managerial, technical, and policy-related.

- *Theoretical Contribution*

The study connects research domains that are frequently treated independently. It combines socio-technical transition theory, organizational readiness, dynamic capabilities, technology acceptance, change management, energy management, and digital transformation within a single enterprise-adoption structure.

This integration extends the conceptualization of sustainable-energy adoption beyond the acquisition of low-carbon equipment. Adoption is treated as a multidimensional transformation in which technical assets, digital systems, organizational structures, employee behavior, governance, and performance-management processes must be jointly aligned. The framework also translates broad socio-technical transition concepts into organization-level mechanisms and implementation stages.

- *Methodological Contribution*

The study develops a structured framework-building method that links evidence synthesis to design requirements, constructs, implementation phases, and validation procedures. It establishes the basis for assessing:

- ✓ Organizational readiness;
- ✓ Digital maturity;
- ✓ Technology suitability;
- ✓ Stakeholder impacts;
- ✓ Implementation risk;
- ✓ Scalability;
- ✓ Energy and emissions performance;
- ✓ Operational performance; and
- ✓ Benefits realization.

These dimensions can subsequently be operationalized through expert-rating instruments, enterprise surveys, technical assessments, implementation records, and energy-performance data. The study therefore provides a foundation for later empirical testing without presenting unvalidated numerical results as observed findings.

- *Managerial Contribution*

For executive leaders, sustainability managers, energy managers, engineering teams, digital-transformation leaders, and facility managers, the framework provides a common

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decision structure. It clarifies how strategic targets can be translated into technology portfolios, capability-development programmes, implementation roadmaps, and measurable outcomes.

The framework also supports cross-functional coordination by identifying decision rights, responsibilities, information requirements, stage-gate criteria, and performance indicators. This can reduce fragmented project selection and strengthen accountability across corporate and site levels.

- *Technical and Operational Contribution*

The proposed framework integrates technical deployment with digital-energy architecture. It recognizes that enterprise adoption requires interoperable metering, reliable data acquisition, standardized asset identification, secure communications, data-quality controls, analytics, visualization, and integration with existing operational systems.

The framework further connects digital information to operational action. Energy data are not treated merely as reporting outputs but as inputs to control, maintenance, forecasting, investment evaluation, and continuous improvement. This provides a basis for ensuring that digitalization produces verifiable energy and operational value.

- *Workforce and Organizational Contribution*

The study gives explicit attention to employees and other affected stakeholders. It incorporates readiness assessment, change-impact analysis, communication, participation, training, role redesign, user support, feedback mechanisms, and reinforcement. This is important because sustained adoption depends on the routines and decisions of equipment operators, engineers, maintenance personnel, managers, procurement teams, and end users.

- *Policy and Regulatory Contribution*

The framework can assist regulators, policymakers, industry associations, and standards bodies in understanding the organizational conditions required for large-scale technology adoption. It may support the design of policies that combine technical incentives with digital readiness, workforce development, measurement requirements, cybersecurity safeguards, and organizational capability building.

➢ *Scope and Delimitations*

The study focuses on the enterprise-wide adoption of sustainable energy technologies within large organizations. Large organizations are understood as entities with substantial operational complexity, multiple departments or facilities, formal governance arrangements, diverse stakeholder groups, and significant energy use or energy-related environmental impacts.

The technological scope includes:

- Renewable electricity and heat;
- Energy-storage systems;
- Industrial and building energy-efficiency technologies;
- Electrification of processes and transport;
- Waste-heat recovery;
- Microgrids and distributed-energy systems;
- Smart meters and advanced metering infrastructure;
- Digitally enabled energy-management platforms;
- IoT-based sensing and control;
- Energy analytics, artificial intelligence, and digital twins; and
- Supporting digital and cybersecurity infrastructure.

The organizational scope covers strategy, leadership, governance, investment decision-making, stakeholder engagement, organizational readiness, workforce competence, technology acceptance, risk management, data governance, implementation, scaling, and performance measurement.

The study is not limited to a specific country, industrial sector, energy technology, vendor, or regulatory jurisdiction. This broad scope supports framework generalizability but requires contextual adaptation during implementation. Technology costs, grid conditions, carbon intensity, regulatory requirements, cybersecurity obligations, workforce characteristics, and organizational structures differ across settings.

The study does not provide detailed engineering designs for individual technologies, equipment specifications, site-specific energy audits, complete life-cycle assessments, or investment-grade financial models. These analyses would require organization-specific technical and financial data. It also does not claim empirical effectiveness because no primary organizational dataset or completed implementation case has been supplied. Any numerical demonstration included later in the paper will therefore be explicitly identified as, hypothetical, simulated, or provisional.

The framework is intended to guide organizational assessment, decision-making, implementation, and validation. It does not replace applicable engineering standards, environmental regulations, energy codes, cybersecurity requirements, financial due diligence, or professional technical judgment.

➢ *Organization of the Paper*

The remainder of the paper is organized into four major sections.

Section 2 presents the literature review. It examines sustainable energy technologies, enterprise digital transformation, digital energy systems, organizational change management, technology acceptance, organizational readiness, dynamic capabilities, socio-technical transitions, empirical adoption studies, implementation barriers, and the resulting research gap.

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Section 3 describes the materials and methods. It explains the design-science approach, structured evidence-synthesis procedure, framework requirements, construct definitions, technology-prioritization method, organizational-readiness assessment, digital-maturity assessment, implementation-risk evaluation, energy and environmental performance measures, and proposed validation procedures.

Section 4 presents and discusses the framework-development results. It introduces the integrated framework architecture, implementation phases, governance structure, digital-energy data architecture, readiness and prioritization mechanisms, stage-gate roadmap, workforce-enablement process, performance dashboard, and an explicitly application. The section also compares the framework with existing approaches and discusses its theoretical and practical implications.

Section 5 summarizes the principal findings, states the conclusion, presents recommendations for organizational leaders and policymakers, acknowledges the study's limitations, and identifies priorities for future empirical research.

II. LITERATURE REVIEW

➢ *Sustainable Energy Technologies in Large Organizations*

Sustainable energy technologies comprise systems that reduce energy consumption, replace carbon-intensive energy sources, improve energy productivity, increase operational flexibility, or enable measurable reductions in greenhouse gas emissions [54], [55]. In large organizations, these technologies can be grouped into five interrelated categories: renewable-energy supply, energy efficiency, electrification, energy storage and flexibility, and digital energy management [56].

Renewable-energy technologies include solar photovoltaic systems, wind energy, geothermal systems, sustainable bioenergy, renewable heat, and power-purchase arrangements that support low-carbon electricity procurement [54], [57]. Energy-efficiency technologies include high-efficiency motors, variable-speed drives, efficient boilers, heat pumps, waste-heat recovery, process integration, efficient lighting, building-envelope improvements, and advanced heating, ventilation, and air-conditioning systems [55], [58]. Electrification replaces direct fossil-fuel consumption with electric technologies where operationally and economically feasible. Energy-storage technologies, microgrids, and demand-response systems improve the organization's ability to coordinate variable renewable generation with operational demand [2], [3], [59].

Sustainable energy adoption in a large organization differs from a single-site equipment replacement. Enterprise adoption requires the coordination of heterogeneous facilities, asset classes, energy markets, operational schedules, procurement processes, and regulatory obligations [56], [60]. It also requires standardized methods for establishing energy baselines, identifying Significant Energy Uses (SEUs), defining Energy Performance Indicators (EnPIs), verifying savings, and comparing performance across sites [61]. ISO 50001:2018 provides a formal Energy Management System (EnMS) structure for these activities [4].

Energy management is broader than energy-efficiency project execution. It includes energy policy, planning, organizational responsibilities, energy review, performance monitoring, employee engagement, procurement, design, and continual improvement [58], [61]. A systematic review of industrial energy-management research identified strategy and planning, implementation, control, organization, and culture as central elements of effective energy management [16]. This indicates that sustainable-energy performance depends on management capabilities as well as equipment efficiency [60], [62].

Technology investment decisions are also influenced by how projects are represented within the organization. Projects framed only as energy-cost reductions may receive lower priority than investments associated with production growth, reliability, quality, safety, or regulatory compliance [63]. Cooremans found that energy-efficiency investment decisions depend partly on the strategic characteristics attributed to the investment, not simply its calculated financial return [17]. Sustainable-energy proposals should therefore incorporate operational resilience, maintenance reduction, productivity, compliance, risk mitigation, and reputational value where these benefits can be credibly demonstrated [62], [64].

The barriers affecting sustainable-energy technologies are interdependent. Cagno et al. classified industrial energy-efficiency barriers according to their origin, affected actor, and relationship with other barriers [18]. For example, imperfect information can increase perceived technical risk, which can produce conservative financial assumptions, weaken management support, and delay procurement [63], [65]. Treating each barrier as an isolated problem can consequently result in incomplete intervention.

For multi-site enterprises, consistency must be balanced with contextual adaptation. Corporate energy policy, data standards, cybersecurity controls, procurement principles, and performance metrics can be standardized, while technical configurations must reflect site-specific demand, climate, infrastructure, tariffs, regulatory conditions, and operational constraints [60], [66]. ISO 50009:2021 provides guidance for implementing a common EnMS across multiple organizations and is relevant to coordinating energy management across subsidiaries, facilities, or organizational units [19]. However, it does not provide a complete digital-transformation or workforce-adoption framework.

Sustainable-energy adoption should therefore be treated as a portfolio transformation rather than a sequence of unrelated capital projects [56], [64]. The portfolio must align technical feasibility, strategic value, financial performance, operational risk, digital compatibility, workforce readiness,

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and scalability [62], [67]. This enterprise perspective provides the foundation for integrating energy management with digital transformation and organizational change.

➢ *Enterprise Digital Transformation*

Digital transformation refers to organization-level change enabled by combinations of digital technologies. It differs from digitization, which converts analogue information into digital form, and digitalization, which applies digital technologies to improve existing activities [68]. Digital transformation involves broader changes to organizational structures, processes, capabilities, value creation, governance, and stakeholder relationships [7], [8], [69].

Enterprise digital transformation is particularly complex in large, asset-intensive organizations. These organizations often operate legacy equipment, fragmented information systems, proprietary industrial protocols, multiple Enterprise Resource Planning (ERP) platforms, and geographically distributed operations [68], [70]. Transformation must therefore connect operational technology, information technology, engineering systems, business processes, and organizational decision-making without compromising reliability, safety, or cybersecurity [66], [71].

Matt et al. proposed that digital-transformation strategy should address four dimensions: use of technologies, changes in value creation, structural changes, and financial aspects [20]. Applied to sustainable energy, these dimensions concern which digital-energy technologies are adopted, how they create energy and operational value, how responsibilities and workflows must change, and how transformation is financed and governed [64], [69].

Verhoef et al. described digital transformation as a multidisciplinary phenomenon involving strategy, organization, information technology, marketing, operations, and broader business ecosystems [21]. This perspective is important because energy transformation cannot be assigned exclusively to engineering or sustainability departments [67], [70]. Its outcomes depend on finance, procurement, operations, information technology, cybersecurity, human resources, facilities management, and executive governance [71], [72].

Digital transformation also has an evolutionary dimension. Nadkarni and Prügl identified recurring relationships between digital technologies, organizational capabilities, and strategic change, while emphasizing that transformation outcomes depend on both technological and managerial factors [22]. Similarly, Warner and Wäger conceptualized digital transformation as an ongoing process of strategic renewal supported by sensing, seizing, and transforming capabilities [9], [69], [73].

In sustainable-energy applications, enterprise digital transformation performs four principal functions. First, it establishes visibility by collecting reliable data on energy flows, operating states, environmental conditions, equipment performance, and production output [68], [72]. Second, it creates analytical capability through forecasting, anomaly detection, optimization, and scenario modelling [74]. Third, it enables coordinated execution by connecting decisions with maintenance, controls, procurement, production planning, and investment management [70], [73]. Fourth, it supports learning by comparing projects, sites, and operating conditions and transferring verified practices across the organization [67], [69].

Digital transformation may nevertheless generate unintended consequences. Increased connectivity expands cybersecurity exposure, while cloud platforms and artificial intelligence systems may increase electricity consumption [71], [75]. Data centralization can create concentration risks, and vendor-specific platforms may produce technological lock-in. The relationship between digital transformation and sustainability is therefore conditional rather than automatically positive [10]. Organizations must evaluate both the sustainability benefits and the environmental, operational, security, and governance costs of digital systems [66], [75].

➢ *Digital Technologies Supporting Sustainable Energy Adoption*

Digital technologies support sustainable-energy adoption by improving measurement, integration, prediction, control, verification, and organizational coordination [68], [72]. Their value arises when data are converted into operationally relevant decisions rather than merely collected for reporting [74], [76].

- *Internet of Things and Advanced Metering*

The Internet of Things (IoT) connects sensors, meters, controllers, equipment, and analytical platforms through communication networks. In energy systems, IoT applications include submetering, asset monitoring, environmental sensing, occupancy detection, demand-response control, distributed-generation monitoring, and equipment-level energy analysis [6], [72], [76].

Advanced metering infrastructure provides time-resolved information on electricity, fuel, steam, compressed air, chilled water, and thermal energy [59], [76]. When meters are installed at appropriate organizational and process boundaries, they allow energy consumption to be allocated to facilities, production lines, equipment, products, or operating shifts. This improves accountability and supports normalized performance evaluation [61], [72].

However, metering density alone does not guarantee useful information. Effective implementation requires an explicit measurement plan, meter hierarchy, time synchronization, calibration requirements, data-quality rules, communications architecture, and responsibility for responding to detected deviations [61], [77]. Poorly structured metering can generate large data volumes without producing actionable insight.

- *Cloud and Edge Computing*

Cloud computing provides scalable storage, processing, analytics, and application services. It can support enterprise

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dashboards, cross-site benchmarking, centralized asset models, and access to advanced analytical tools [68], [74]. Edge computing performs selected processing close to the equipment or facility, reducing latency, bandwidth demand, and dependence on continuous external connectivity [71], [77].

A hybrid cloud-edge architecture is often appropriate for large organizations. Safety-critical and time-sensitive controls remain at the site or edge, while aggregated data, portfolio analytics, and corporate reporting can be processed centrally [70], [71]. The allocation of functions between edge and cloud environments should reflect operational criticality, latency, data sovereignty, cybersecurity, availability, and cost [75], [77].

- *Artificial Intelligence and Machine Learning*

Artificial Intelligence (AI) and Machine Learning (ML) can support energy-load forecasting, fault detection, predictive maintenance, renewable-generation forecasting, equipment optimization, tariff response, and control of flexible loads [74], [78]. These applications can improve decision speed and identify nonlinear relationships that are difficult to detect through manual analysis.

The value of AI depends on data quality, model validity, interpretability, integration, and human oversight [76], [78]. A model trained on incomplete, biased, or nonrepresentative operating data may recommend actions that are technically inappropriate. Model performance must therefore be monitored after deployment, particularly when equipment, production schedules, energy tariffs, or environmental conditions change [77], [79].

AI should be applied where it provides a demonstrable advantage over simpler analytical methods. Not every energy problem requires an advanced predictive model. Rules-based alarms, statistical process control, regression models, or conventional optimization may provide more transparent and maintainable solutions for stable processes [74], [79].

- *Digital Twins and Simulation*

A digital twin is a digital representation of a physical asset, process, facility, or system that is updated using operational data [73], [80]. Digital twins can be used to simulate energy-system configurations, compare operating strategies, predict performance, evaluate equipment degradation, and support commissioning.

For sustainable-energy adoption, digital twins can reduce implementation uncertainty by testing interactions among renewable generation, storage, production demand, utility constraints, and control strategies before physical modification [59], [80]. They can also support continuous commissioning by comparing observed performance with the expected behaviour of the asset or process [74], [80].

Digital twins require disciplined model governance. The organization must define the twin's purpose, model boundary, update frequency, data inputs, validation criteria, and acceptable uncertainty [77], [80]. A visually sophisticated model that is not calibrated against reliable operating data may create false confidence.

- *Cyber-Physical Systems and Automated Control*

Cyber-Physical Systems (CPS) integrate computation, communications, sensing, and physical processes [70], [81]. In industrial environments, CPS can support coordinated energy control across equipment, production lines, buildings, storage systems, and distributed generation. The five-level CPS architecture proposed by Lee et al. progresses from connection and data conversion to cyber-level aggregation, cognition, and configuration [24].

Automation can convert analytical insight into operational action. Examples include automated adjustment of motor speed, thermal setpoints, equipment sequencing, battery dispatch, and demand-response participation [59], [76], [81]. These functions should be constrained by safety, quality, reliability, and production requirements. Energy optimization must not override critical process limits or protection systems [71], [81].

- *Blockchain and Distributed-Ledger Applications*

Blockchain and related distributed-ledger technologies may support renewable-energy certificate tracking, peer-to-peer energy transactions, asset provenance, carbon-data traceability, and automated contractual execution [57], [82]. Their relevance depends on whether multiple parties require a shared and tamper-evident record without relying on a single trusted intermediary.

Blockchain should not be adopted where a conventional secured database can provide the required functionality more efficiently. Its computational requirements, governance complexity, privacy implications, transaction speed, and integration costs must be assessed against the intended value [75], [82].

- *Industry 4.0 and Sustainable Operations*

Industry 4.0 integrates IoT, CPS, automation, cloud computing, analytics, and digitally connected production systems [70], [76]. Ghobakhloo identified several pathways through which Industry 4.0 may support sustainability, including resource optimization, improved asset utilization, reduced defects, predictive maintenance, and more responsive production [23].

These benefits are contingent on implementation quality. Digital technologies can improve energy efficiency while simultaneously increasing equipment complexity and electricity demand [10], [75]. The net sustainability effect should therefore be measured using explicit boundaries and performance indicators [61], [76].

➢ *Organizational Change Management*

Organizational Change Management (OCM) is the structured process of preparing, supporting, and enabling individuals, teams, and institutions to move from a current state to a defined future state [62], [65]. In sustainable-energy transformation, OCM addresses changes in roles, workflows,

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decision rights, competencies, technologies, performance expectations, and organizational culture [67], [69].

Change management is necessary because sustainable-energy systems alter more than physical infrastructure. A new energy platform may require operators to respond to digital alerts, maintenance teams to use condition-based work orders, finance teams to apply new investment criteria, and managers to accept greater transparency in facility performance [64], [72]. These changes may affect autonomy, workload, established routines, professional identity, and perceived accountability [65], [69].

Armenakis et al. distinguished readiness for change from resistance and emphasized that readiness is influenced by organizational members' beliefs, attitudes, and intentions [25]. A credible change message should explain why the change is necessary, why the proposed solution is appropriate, whether the organization is capable of implementation, whether leaders support the change, and how affected individuals will benefit or be protected [62], [67].

Change-management processes commonly include:

- Establishing a credible rationale for change;
- Defining the target state and expected benefits;
- Identifying affected stakeholders;
- Assessing change impacts and readiness;
- Establishing visible leadership sponsorship;
- Involving users in solution design;
- Communicating role-specific information;
- Developing required knowledge and competencies;
- Providing implementation support;
- Monitoring adoption and performance; and
- Reinforcing new routines through governance, recognition, and accountability [62], [65], [69].

The quality of participation is particularly important. Employees who operate or maintain energy-intensive systems possess practical knowledge about equipment constraints, production variability, safety risks, and informal workarounds [58], [67]. Excluding them from design can result in technically plausible systems that are difficult to operate. Participation should nevertheless be structured. It should inform decisions without creating ambiguity over engineering authority, risk acceptance, or regulatory responsibility [66], [71].

Change communication must also be differentiated by stakeholder group. Executive leaders require strategic, financial, and risk information. Facility managers require performance responsibilities and resource implications. Operators require clear explanations of workflow changes and system benefits. Information-technology and cybersecurity personnel require architecture, access, and control requirements [65], [70]. Generic communication is unlikely to address these distinct concerns [67], [69].

➢ *Employee Acceptance and Resistance to Technological Change*

Employee acceptance determines whether installed technologies are used consistently and as intended [65], [69]. Adoption is not equivalent to technical availability. A digital energy platform may be commissioned successfully but deliver limited value if users ignore alerts, maintain parallel spreadsheets, bypass automated functions, or distrust model recommendations [67], [78].

The Unified Theory of Acceptance and Use of Technology identifies performance expectancy, effort expectancy, social influence, and facilitating conditions as core determinants of behavioural intention and use [14]. In sustainable-energy systems:

- Performance expectancy concerns whether users believe the technology will improve work quality, energy performance, reliability, safety, or decision-making.
- Effort expectancy concerns the perceived difficulty of learning and operating the system.
- Social influence concerns whether managers, peers, specialists, and professional groups support its use.
- Facilitating conditions concern the availability of training, technical support, infrastructure, time, access, and compatible work processes [65], [69].

Resistance should not automatically be interpreted as irrational opposition. Oreg conceptualized resistance as a multidimensional response involving affective, behavioural, and cognitive elements [29]. Employees may resist because they anticipate job displacement, increased monitoring, reduced autonomy, additional workload, technical failure, safety consequences, or unfair performance evaluation [65], [78]. Some resistance may reveal legitimate system defects or implementation risks.

Resistance can occur at several levels. Individual resistance arises from perceived loss, low confidence, limited competence, or preference for existing routines. Group resistance can emerge where a technology conflicts with professional norms or established team practices. Structural resistance occurs when policies, incentives, budgets, or reporting relationships support the existing state. Political resistance may arise when the technology redistributes information, resources, or decision authority [62], [67], [69].

Employee acceptance should therefore be managed through diagnosis rather than persuasion alone. Relevant interventions include user participation, role-specific training, practical demonstrations, local champions, accessible support, phased deployment, transparent explanation of data use, and rapid correction of usability problems [65], [67]. Organizations should also identify whether non-use results from unwillingness, inability, lack of access, poor workflow integration, or rational concern about system reliability [69], [78].

Holt et al. developed a systematic measure of readiness for organizational change based on beliefs about change appropriateness, management support, change efficacy, and

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personal value [30]. These dimensions are useful for assessing whether employees understand the sustainable-energy initiative, believe leaders are committed, feel capable of performing new requirements, and perceive the change as compatible with their interests [62], [65].

➢ *Organizational Readiness and Digital Capability*

Organizational readiness refers to the collective willingness and capability to implement a proposed change. Weiner described readiness as a shared state comprising change commitment and change efficacy [13]. Commitment reflects the organization's resolve to pursue the change, while efficacy reflects confidence in its ability to execute the required actions [62], [67].

Readiness for sustainable-energy transformation has several dimensions:

- Strategic readiness: Clarity of energy and sustainability objectives, executive sponsorship, and alignment with business priorities [56], [64].
- Governance readiness: Defined decision rights, accountability, escalation procedures, and cross-functional coordination [60], [67].
- Financial readiness: Access to capital, appropriate investment criteria, benefits-tracking capability, and tolerance for technology and market uncertainty [63], [64].
- Technical readiness: Suitable infrastructure, engineering competence, asset condition, and system compatibility [58], [66].
- Digital readiness: Data availability, interoperability, architecture, analytics, cybersecurity, and technical support [68], [71].
- Workforce readiness: Awareness, competence, participation, workload capacity, and willingness to adopt new practices [62], [65].
- Operational readiness: Capacity to pilot, commission, maintain, and scale technologies without unacceptable disruption [60], [67].
- Regulatory readiness: Knowledge of applicable requirements, permitting, reporting, and compliance controls [61], [66].

Digital capability is a related but distinct construct. It represents the organization's ability to mobilize digital resources to achieve operational and strategic objectives [68], [73]. It includes infrastructure, data governance, architecture, cybersecurity, digital skills, analytical competence, innovation processes, and the ability to redesign work [69], [71].

Digital maturity assessments often focus on the presence or sophistication of technologies. This can be misleading because an organization may possess advanced platforms but lack data quality, user adoption, cross-functional governance, or benefits realization [68], [77]. Capability should therefore be evaluated by what the organization can reliably accomplish, not simply by what technologies it owns [69], [73].

Readiness is also technology- and context-specific. An organization may be ready to deploy smart meters but not ready to use automated demand-response controls. It may have strong central analytics capability but weak site-level maintenance capacity [59], [76]. Readiness assessment should consequently be performed at enterprise, facility, process, stakeholder, and technology levels [62], [67].

➢ *Theoretical Foundations*

No single theory adequately explains the enterprise adoption of sustainable energy technologies. The proposed study therefore combines five complementary perspectives. Their relationships are summarized in Table 1.

Table 1 Theoretical Foundations for Enterprise Sustainable-Energy Adoption

Theory	**Primary analytical focus**	**Principal constructs**	**Application to the study**	**Limitation when applied independently**
Socio-Technical Systems Theory	Joint design of social and technical subsystems	People, technology, tasks, structure, environment, joint optimization	Aligns energy technologies, digital systems, work processes, governance, and users	Provides limited guidance on investment prioritization and diffusion rate
Dynamic Capabilities Theory	Organizational adaptation under changing conditions	Sensing, seizing, transforming	Explains how organizations identify, invest in, and scale sustainable-energy opportunities	Gives limited attention to individual user acceptance
Unified Theory of Acceptance and Use of Technology	Individual acceptance and use	Performance expectancy, effort expectancy, social influence, facilitating conditions	Explains employee intention and use of digital-energy systems	Primarily user-level and may underrepresent institutional and engineering factors
Diffusion of Innovations Theory	Spread of innovations over time and across a social system	Relative advantage, compatibility, complexity, trialability, observability	Supports pilot design, communication, champion networks, and enterprise scaling	Does not fully specify governance, cybersecurity, or organizational capability

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Institutional Theory	External and internal pressures shaping organizational behavior	Coercive, normative, and mimetic pressures; legitimacy	Explains effects of regulation, professional standards, investor expectations, and peer practices	May overemphasize conformity and underexplain operational execution

- *Socio-Technical Systems Theory*

Socio-Technical Systems (STS) Theory proposes that organizational performance depends on the joint optimization of social and technical subsystems. Technical optimization without corresponding attention to roles, incentives, knowledge, communication, and work design can reduce overall system performance. Baxter and Sommerville emphasized that socio-technical design must consider the interaction among technological systems, people, organizational processes, and the operating environment [31].

This theory is directly applicable to digitally enabled sustainable-energy systems. A technically accurate energy-optimization platform may fail if operators cannot interpret its recommendations, managers are not accountable for response, or maintenance systems cannot implement corrective work. Conversely, strong employee engagement cannot compensate for inaccurate meters, unreliable communications, or poor equipment controls.

The STS perspective supports participatory design, role clarification, task redesign, human oversight, and the assessment of unintended consequences. It provides the integrating logic for treating energy assets, digital platforms, employees, organizational structures, and environmental conditions as one implementation system.

- *Dynamic Capabilities Theory*

Dynamic Capabilities Theory explains how organizations adapt resources and competencies in rapidly changing environments. Teece organized dynamic capabilities around the activities of sensing opportunities and threats, seizing opportunities through investment and organizational commitment, and transforming or reconfiguring resources to sustain performance [32].

For sustainable energy adoption, sensing includes identifying technology developments, policy changes, energy-price exposure, operational inefficiencies, and stakeholder expectations. Seizing includes selecting technologies, mobilizing capital, establishing partnerships, and designing business cases. Transforming includes redesigning operations, integrating digital platforms, developing competencies, changing governance, and scaling successful configurations.

Warner and Wäger applied dynamic-capabilities reasoning to digital transformation and emphasized continual strategic renewal [9]. This is relevant because sustainable-energy transformation is not a one-time programme. Technology maturity, regulation, energy markets, climate risks, and organizational priorities continue to evolve after initial implementation.

- *Unified Theory of Acceptance and Use of Technology*

The Unified Theory of Acceptance and Use of Technology provides an individual- and group-level explanation of technology acceptance [14]. It is included because enterprise transformation ultimately depends on repeated use by operators, engineers, managers, analysts, and other stakeholders.

The theory informs the design of the employee-adoption component of the framework. Performance expectancy guides the communication of role-specific value. Effort expectancy supports usability assessment and training design. Social influence highlights leadership behavior, peer norms, and local champions. Facilitating conditions direct attention to infrastructure, support, time, access, and compatible procedures.

The theory does not fully explain capital allocation, technical integration, or external regulation. It is therefore combined with organizational and institutional perspectives.

- *Diffusion of Innovations Theory*

Diffusion of Innovations Theory explains how an innovation spreads through communication channels over time among members of a social system. Rogers identified relative advantage, compatibility, complexity, trialability, and observability as important attributes affecting adoption [33].

Relative advantage concerns whether the sustainable-energy technology is perceived as better than the current alternative. Compatibility concerns alignment with existing infrastructure, values, work processes, and technical standards. Complexity affects the effort required for adoption. Trialability supports controlled pilots before full-scale investment. Observability enables stakeholders to see and verify benefits.

The theory also distinguishes adopter categories, including innovators, early adopters, the early majority, the late majority, and laggards. In a large organization, these categories can be reflected in facilities, departments, managers, or professional groups. Enterprise scaling can use credible early adopters and reference sites to reduce uncertainty for later adopters. However, the sequence should be based on readiness and operational suitability rather than a simplistic expectation that every facility will follow the same adoption path.

- *Institutional Theory*

Institutional Theory explains how organizational behavior is shaped by pressures for legitimacy and conformity. DiMaggio and Powell identified coercive, normative, and mimetic mechanisms of institutional isomorphism [34].

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Coercive pressures arise from laws, regulations, permits, parent-company requirements, lender conditions, and contractual obligations. Normative pressures arise from professional standards, certification systems, engineering norms, and stakeholder expectations. Mimetic pressures occur when organizations imitate peers perceived as legitimate or successful, particularly under uncertainty.

Institutional pressures can accelerate sustainable-energy adoption by strengthening executive attention, directing capital, and establishing common expectations. However, they can also produce symbolic adoption, where policies, certifications, or technologies are implemented to demonstrate legitimacy without achieving substantial operational change. The proposed framework therefore connects institutional commitment with measurable implementation and performance evidence.

➢ *Existing Change-Management Models*

Several established change-management models provide useful but partial guidance for sustainable-energy transformation.

Lewin's planned-change model is commonly represented through unfreezing, changing, and refreezing. Unfreezing challenges the existing equilibrium and establishes readiness. Changing introduces new practices and behaviors. Refreezing stabilizes the new state. Burnes' reappraisal of Lewin's work explains that the model forms part of a broader field-theoretical and participative approach rather than merely a rigid three-stage sequence [26].

For sustainable-energy adoption, unfreezing may involve demonstrating energy risk, performance gaps, regulatory exposure, or strategic opportunity. Changing includes technology deployment, workflow redesign, training, and role transition. Refreezing involves integrating new practices into procedures, performance management, maintenance systems, budgets, and organizational norms. Its principal limitation is that digital and energy transformations often require continuous adaptation rather than a stable final state.

Kotter's model comprises establishing urgency, forming a guiding coalition, developing a vision and strategy, communicating the vision, empowering action, generating short-term wins, consolidating gains, and anchoring change in organizational culture [27]. The model is useful for executive alignment and enterprise mobilization. Short-term wins are particularly relevant to energy pilots because verified savings can strengthen confidence and funding. However, the model provides limited technical guidance for data architecture, technology evaluation, energy-performance normalization, and cybersecurity.

The Awareness, Desire, Knowledge, Ability, and Reinforcement (ADKAR) model focuses on individual transition [28]. Awareness concerns understanding the need for change; desire concerns willingness to participate; knowledge concerns knowing how to change; ability concerns practical execution; and reinforcement concerns sustaining the change. ADKAR is useful for diagnosing employee-adoption problems but does not independently address enterprise architecture, project portfolio governance, or external institutional pressures.

Evidence-based reviews caution against applying change models as universally valid sequences. Stouten et al. found that successful planned change depends on evidence-supported mechanisms such as diagnosis, leadership, participation, communication, goal setting, support, reinforcement, and evaluation [15]. The proposed study therefore extracts compatible mechanisms from existing models rather than adopting one model without modification.

➢ *Existing Digital-Transformation Frameworks*

Existing digital-transformation frameworks provide valuable strategic constructs but differ in scope and level of analysis.

Vial's framework identifies digital technologies as disruptions that generate strategic responses, changes in value-creation paths, structural changes, organizational barriers, and positive or negative outcomes [7]. Its strength lies in connecting technology-driven disruption with organizational change. However, it is intentionally broad and does not provide a detailed implementation method for sustainable-energy technologies.

Matt et al.'s digital-transformation strategy framework emphasizes technology use, value creation, structural change, and financial considerations [20]. It offers a concise structure for strategic alignment but provides limited detail on workforce adoption, energy engineering, measurement and verification, and cross-site implementation.

Verhoef et al. distinguish digitization, digitalization, and digital transformation and connect them with organizational resources, growth strategies, structures, and performance metrics [21]. The framework highlights the multidisciplinary character of transformation but is oriented substantially toward markets, customers, and business-model outcomes.

Warner and Wäger's dynamic-capability model identifies microfoundations for digital sensing, digital seizing, and digital transformation [9]. It explains how incumbent firms develop agility and renew business models, collaborative arrangements, and organizational culture. Its process orientation is valuable for enterprise energy adoption, although energy-specific technical and environmental-performance criteria must be added.

ISO 50001 provides a Plan-Do-Check-Act management-system structure for continual energy-performance improvement [4]. ISO 50009 extends common energy-management principles to multi-organization arrangements [19]. These standards strengthen energy governance and performance management but do not provide a complete digital-transformation or employee-adoption architecture.

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Table 2 Comparison of Existing Approaches Relevant to the Proposed Framework

Approach	Strategic alignment	Technology architecture	Workforce adoption	Energy-performance measurement	Enterprise scaling	Principal limitation
Lewin planned change	Moderate	Low	High	Low	Low	Assumes a comparatively defined transition state
Kotter eight-stage model	High	Low	High	Low	Moderate	Limited engineering and data guidance
ADKAR	Low	Low	High	Low	Low	Focuses mainly on individual change
Vial digital-transformation framework	High	Moderate	Moderate	Low	Moderate	Broad conceptual scope
Matt et al. digital-transformation strategy	High	Moderate	Low	Low	Moderate	Limited implementation and adoption detail
Warner and Wäger dynamic-capability model	High	Moderate	Moderate	Low	High	Not specific to sustainable-energy systems
ISO 50001/ISO 50009	High	Low–Moderate	Moderate	High	High	Limited digital-transformation and behavioral detail
Proposed integrated framework	High	High	High	High	High	Requires empirical validation

Table 2 shows that no reviewed approach fully integrates change mechanisms, digital architecture, energy-performance management, and enterprise scaling. This is not necessarily a defect in the individual frameworks because they were developed for different purposes. It nevertheless creates a practical integration requirement for large organizations.

- *Empirical Evidence on Enterprise Sustainable-Energy Adoption*

Empirical research indicates that sustainable-energy adoption is shaped by organizational decision processes as strongly as by technical performance.

Wang et al. investigated sustainable-energy technology adoption among large organizations in California and identified institutional barriers affecting organizational purchasing and implementation decisions [11]. Their findings reinforce the importance of policy design, organizational buying behavior, information, and decision structures. Large organizations may possess capital and technical expertise while still experiencing delays caused by internal procedures, competing priorities, and risk allocation.

Cooremans demonstrated that investment characteristics and strategic framing affect energy-efficiency decisions [17]. This explains why projects with apparently attractive savings can remain unfunded. Financial metrics are frequently evaluated alongside perceived strategic relevance, production impact, risk, and organizational visibility.

Cagno et al. showed that industrial energy-efficiency barriers involve interacting economic, organizational, behavioral, competence, technological, and informational mechanisms [18]. Their taxonomy suggests that interventions should be barrier-specific. Training cannot resolve a capital constraint, while financing alone cannot resolve poor data quality or operational distrust.

Schulze et al.'s systematic review found that energy-management performance depends on formal strategy, organizational arrangements, implementation practices, control systems, and culture [16]. Energy-management maturity therefore involves both formal systems and routine organizational behavior.

Evidence from Ghanaian industry identified access to capital, weak policy frameworks, limited technical competence, information constraints, and other organizational conditions as barriers to industrial energy-efficiency improvement [35]. This evidence is important for the framework's contextual adaptability because the relative importance of barriers varies across regulatory, infrastructural, and economic environments.

The empirical literature collectively supports four conclusions. First, technically and financially attractive opportunities may remain unimplemented. Second, adoption barriers interact and should not be managed independently. Third, management practices and organizational capabilities influence sustained energy performance. Fourth, regulatory

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and institutional context affects both incentives and implementation capacity.

However, much of the empirical evidence focuses on adoption determinants, barriers, individual projects, or energy-management practices. Fewer studies examine how change management, digital architecture, organizational readiness, and technology scaling interact throughout the complete enterprise-adoption lifecycle.

➢ *Technical, Financial, Organizational, Regulatory, and Behavioral Barriers*

* *Technical Barriers*

Technical barriers include legacy-system incompatibility, inadequate metering, poor asset condition, limited grid capacity, intermittent renewable generation, insufficient storage, equipment integration difficulty, data-quality problems, and lack of interoperability. Proprietary protocols and vendor-specific platforms can prevent data exchange across facilities.

Technology maturity and site suitability also vary. A technology proven in one operating environment may not perform similarly under different climatic, process, maintenance, or grid conditions. Organizations may therefore perceive deployment risk even where the underlying technology is commercially available.

Cybersecurity is a further technical barrier. Increased connectivity creates additional attack surfaces and introduces dependencies among energy assets, operational networks, cloud services, and enterprise information systems. Cybersecurity requirements should be incorporated at the architecture and procurement stages rather than added after deployment.

* *Financial Barriers*

Financial barriers include high initial capital cost, restricted budgets, short payback requirements, uncertainty in energy prices, difficulty monetizing non-energy benefits, and competition with production-related investments. Conventional investment analysis may undervalue resilience, risk reduction, avoided emissions, maintenance savings, and regulatory preparedness [17].

Split incentives may also occur. A corporate unit may provide capital while a facility receives the savings, or a landlord may invest while a tenant benefits. Without appropriate allocation and performance mechanisms, the responsible decision-maker may have limited incentive to approve the project.

Financing constraints should be distinguished from financial-evaluation constraints. An organization may have access to capital but use investment rules that systematically disadvantage energy projects. Appropriate responses may include portfolio funding, internal carbon pricing, revolving energy funds, performance contracting, or revised evaluation criteria, subject to organizational policy and verified project conditions.

* *Organizational Barriers*

Organizational barriers include fragmented ownership, weak leadership support, competing priorities, slow decision processes, limited cross-functional coordination, unclear accountability, insufficient staffing, and absence of standardized implementation procedures. Energy responsibility may be assigned to personnel without corresponding authority, budgets, or data access.

Pilot projects may also become isolated from enterprise governance. A successful facility-level initiative may rely on individual champions, temporary vendor support, or locally developed data structures that cannot be replicated. Enterprise scaling requires documentation, standardization, reusable architecture, resource planning, and ownership beyond the original project team.

* *Regulatory and Institutional Barriers*

Regulatory barriers include uncertain policies, complex permitting, inconsistent technical codes, changing incentives, grid-connection delays, data-localization requirements, and ambiguous treatment of distributed energy resources. Regulatory conditions may vary across jurisdictions within the same enterprise.

Institutional pressures can encourage adoption through mandatory requirements, voluntary standards, investor expectations, and peer comparison. However, compliance-oriented adoption may prioritize formal documentation over operational outcomes. The framework should therefore connect compliance evidence with measurable energy and environmental performance.

* *Behavioral and Cultural Barriers*

Behavioral barriers include resistance to altered routines, low trust in automated recommendations, risk aversion, limited environmental awareness, fear of job displacement, and reluctance to share data. Organizational culture influences whether employees report problems, experiment with new methods, collaborate across functions, and learn from unsuccessful pilots.

Incentives can produce unintended behavior. If production volume is rewarded without consideration of energy performance, operators may reasonably prioritize throughput over energy optimization. Conversely, poorly designed energy targets may encourage actions that reduce reported consumption while compromising quality, safety, or maintenance. Sustainable-energy performance indicators must therefore be integrated with operational objectives.

* *Knowledge and Capability Barriers*

Knowledge barriers include limited engineering expertise, insufficient data literacy, weak change-management competence, lack of cybersecurity knowledge, and inability to evaluate vendors or analytical models. These deficiencies may increase dependence on external consultants and reduce the organization’s ability to maintain or scale implemented solutions.

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Capability development should address different roles. Executives require portfolio and risk understanding; engineers require technology and integration competence; analysts require data and model-governance skills; operators require practical system use; and procurement teams require appropriate technical and contractual criteria.

➢ *Limitations of Existing Frameworks*

Existing frameworks exhibit five principal limitations when applied to enterprise sustainable-energy adoption.

First, they are frequently domain-specific. Energy-management frameworks emphasize performance improvement, change models emphasize people and behavior, and digital-transformation frameworks emphasize strategy and technology. Their constructs are rarely connected through a single implementation architecture.

Second, many frameworks operate at one analytical level. Technology-acceptance models focus primarily on individuals, energy standards focus on organizational management systems, and socio-technical transition theories often address sectoral or societal change. Enterprise adoption requires individual, team, facility, corporate, ecosystem, and institutional levels to be considered together.

Third, existing frameworks provide insufficient integration between readiness and technology prioritization. A project may be ranked highly on technical or financial criteria while the organization lacks the infrastructure, competence, governance, or stakeholder commitment required for successful implementation.

Fourth, many frameworks treat implementation as a project rather than a learning system. Enterprise scaling requires feedback between pilot results, architecture standards, workforce capability, investment criteria, and future project selection. Without this feedback, organizations repeatedly encounter the same integration and adoption problems.

Fifth, environmental performance is often treated as an outcome separate from digital and organizational performance. A complete framework should connect technology use, user adoption, process execution, energy performance, emissions reduction, financial value, and organizational learning.

➢ *Research Gap*

The literature establishes that sustainable-energy adoption is influenced by technical feasibility, financial evaluation, organizational capability, employee behavior, and institutional conditions. It also demonstrates that digital technologies can improve energy visibility, prediction, control, and verification. However, three research streams remain insufficiently integrated.

The first stream addresses sustainable-energy and industrial energy-efficiency adoption. It identifies barriers, drivers, investment characteristics, and energy-management practices but provides limited guidance on digital transformation and employee transition.

The second stream addresses enterprise digital transformation. It explains strategic renewal, organizational reconfiguration, and digital capability but rarely incorporates energy-engineering requirements, EnPIs, energy baselines, measurement and verification, or emissions performance.

The third stream addresses organizational change and technology acceptance. It explains readiness, resistance, leadership, communication, participation, and system use but generally does not include technology-portfolio prioritization, interoperable energy-data architecture, or multi-site scaling.

Consequently, the literature lacks an empirically testable framework that jointly specifies:

- Sustainable-energy technology selection;
- Enterprise and facility readiness;
- Digital maturity and architecture;
- Organizational change mechanisms;
- Stakeholder acceptance;
- Implementation governance;
- Pilot-to-scale transition;
- Energy and emissions measurement;
- Benefits realization; and
- Continuous organizational learning.

This gap is particularly relevant to large organizations because their structural complexity magnifies the consequences of fragmented governance, incompatible systems, and uneven site readiness.

➢ *Proposed Conceptual Integration*

The proposed conceptual integration treats sustainable-energy adoption as an enterprise socio-technical transformation process. It combines five analytical layers.

- *External and Strategic Context*

The first layer comprises regulation, energy markets, stakeholder expectations, technology development, climate commitments, organizational strategy, and operational risk. These factors create adoption pressure and define the strategic value of sustainable-energy technologies.

Institutional Theory explains the external pressures, while Dynamic Capabilities Theory explains how the organization senses and interprets them.

- *Organizational Readiness and Capability*

The second layer comprises leadership commitment, governance, finance, technical infrastructure, digital maturity, workforce competence, and implementation capacity. These factors determine whether the organization can convert strategic intent into coordinated action.

Organizational-readiness theory explains commitment and efficacy, while Dynamic Capabilities Theory explains resource mobilization and reconfiguration.

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- *Technology and Digital Architecture*

The third layer comprises sustainable-energy assets, metering, communications, data platforms, analytics, digital twins, control systems, cybersecurity, interoperability, and system integration. This layer provides the technical basis for deployment and performance management.

Socio-Technical Systems Theory requires these elements to be designed jointly with roles, tasks, decision rights, and human oversight.

- *Change and Adoption Mechanisms*

The fourth layer comprises stakeholder analysis, communication, participation, training, local champions, user support, feedback, and reinforcement. These mechanisms influence employee acceptance and the incorporation of technologies into routine work.

The Unified Theory of Acceptance and Use of Technology explains user behavior, while Diffusion of Innovations Theory informs pilot design, observability, peer influence, and enterprise scaling.

- *Performance and Organizational Learning*

The fifth layer comprises adoption indicators, energy performance, emissions reduction, financial value, operational reliability, cybersecurity performance, stakeholder outcomes, and lessons learned. Performance data are fed back into project prioritization, architecture standards, capability development, and governance.

The proposed integration therefore follows a closed-loop structure:

- ✓ Diagnose the external environment and current organizational state;
- ✓ Align the transformation with strategy and governance;
- ✓ Assess readiness and prioritize technologies;
- ✓ Co-design technical and organizational solutions;
- ✓ Pilot and validate under controlled conditions;
- ✓ Scale through reusable standards and capabilities; and
- ✓ Institutionalize performance measurement and continuous improvement.

The conceptual relationships can be expressed through the following propositions:

- ✓ P1: Strategic alignment positively influences executive commitment and resource allocation for sustainable-energy adoption.
- ✓ P2: Organizational readiness positively influences implementation quality and adoption continuity.
- ✓ P3: Digital capability strengthens the relationship between sustainable-energy investment and measurable energy performance.
- ✓ P4: Socio-technical alignment positively influences employee acceptance and operational integration.
- ✓ P5: Employee acceptance mediates the relationship between change-management interventions and sustained technology use.
- ✓ P6: Verified pilot performance and outcome visibility positively influence enterprise diffusion and scaling.
- ✓ P7: Regulatory clarity and institutional support strengthen the relationship between organizational capability and technology adoption.
- ✓ P8: Continuous performance feedback strengthens organizational learning and subsequent portfolio decisions.

These propositions provide a testable basis for the methodology and validation procedures developed in Section 3.

III. MATERIALS AND METHODS

- ➢ *Research Philosophy and Design*

This study adopts a pragmatic research philosophy because its primary purpose is to develop a usable organizational framework for addressing a complex implementation problem. Pragmatism permits the integration of qualitative evidence, quantitative decision models, technical performance indicators, and organizational assessment methods according to their relevance to the research problem.

The study uses an abductive reasoning process. Existing theories and empirical evidence provide the initial constructs, while the framework-development process reorganizes these constructs into an integrated implementation architecture. The resulting framework generates propositions and measurement variables that can subsequently be tested using expert assessment, organizational surveys, case studies, and longitudinal implementation data.

The research design combines four methodological components:

- Structured integrative literature review;
- Design-Science Research (DSR);
- Multi-Criteria Decision Analysis (MCDA); and
- Proposed mixed-method framework validation.

DSR is appropriate because the principal research output is an artifact comprising constructs, assessment instruments, decision models, implementation processes, governance mechanisms, and performance measures. Design-science research emphasizes the development and evaluation of artifacts intended to solve relevant organizational problems [36]. The study follows the problem-identification, objective-definition, design, demonstration, evaluation, and communication sequence proposed by Peffers et al. [37].

The present paper develops the conceptual artifact and validation protocol. It does not claim measured organizational effects because primary enterprise data, completed expert responses, and longitudinal implementation records have not been supplied.

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➢ *Design-Science Research Process*

The framework-development process consists of six iterative stages presented in Table 3.

Table 3 Design-Science Research Stages Used in Framework Development

Stage	Principal activity	Input	Output
1. Problem identification	Define the fragmented adoption problem	Literature, standards, organizational adoption barriers	Formal problem statement
2. Design-objective definition	Specify required framework capabilities	Research gap, theories, implementation requirements	Design requirements
3. Artifact construction	Integrate constructs, processes, measures, and decision rules	Evidence synthesis and theoretical foundations	Initial framework
4. Demonstration	Apply the framework to structured scenarios or organizational cases	Technology and organizational input data	Priorities, readiness scores, risks, and roadmap
5. Evaluation	Assess relevance, validity, usability, consistency, and sensitivity	Expert ratings, case evidence, user feedback	Validated and refined framework
6. Communication	Document framework logic, procedures, limitations, and applications	Evaluation results	Final research and practitioner outputs

Iteration is permitted between stages. For example, expert evaluation may identify missing design requirements, requiring revision of the constructs, scoring criteria, or implementation sequence. Version control should be maintained so that every material change to the framework can be traced to supporting evidence or validation feedback.

The artifact is evaluated against five high-level criteria:

- Relevance: whether the framework addresses recognized enterprise adoption problems;
- Completeness: whether it contains the technical, organizational, digital, financial, and regulatory components required for implementation;
- Internal consistency: whether constructs, equations, decision rules, and implementation stages are logically compatible;
- Usability: whether intended organizational users can apply the framework without unreasonable complexity; and
- Utility: whether its use improves decision transparency, implementation readiness, adoption, or performance measurement.

➢ *Structured Literature-Review Protocol*

The literature-review stage uses a structured integrative approach because the study combines empirical articles, conceptual research, technical standards, and authoritative institutional guidance. Integrative reviews are suitable for synthesizing heterogeneous evidence and generating new conceptual structures [39].

The review protocol follows the reporting principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement where applicable [38]. The review is not presented as a meta-analysis because the included studies differ substantially in research design, constructs, technologies, industries, and reported outcomes.

The proposed databases are:

- Scopus;
- Web of Science Core Collection;
- IEEE Xplore;
- ScienceDirect;
- Business Source Complete; and
- Google Scholar for supplementary citation tracing.

Authoritative technical sources are obtained directly from organizations such as the International Organization for Standardization, International Energy Agency, Intergovernmental Panel on Climate Change, National Institute of Standards and Technology, Greenhouse Gas Protocol, and Efficiency Valuation Organization.

The principal search concept is divided into four blocks:

- Energy Technology: “sustainable energy,” “renewable energy,” “energy efficiency,” “energy management,” “electrification,” “energy storage,” and “low-carbon technology”;
- Organizational Adoption: “enterprise adoption,” “organizational adoption,” “technology implementation,” “organizational readiness,” “employee acceptance,” and “resistance to change”;
- Digital Transformation: “digital transformation,” “Internet of Things,” “artificial intelligence,” “digital twin,” “energy analytics,” “cyber-physical system,” and “digital maturity”; and
- Change Management: “organizational change,” “change management,” “stakeholder engagement,” “technology acceptance,” and “capability development.”

A representative Boolean search string is: (“sustainable energy” OR “renewable energy” OR “energy efficiency” OR “energy management”) AND (“digital transformation” OR “digital technology” OR “Internet of Things” OR “energy analytics”) AND (“change management” OR “organizational readiness” OR “technology adoption” OR “employee

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acceptance") AND ("enterprise" OR "organization" OR "industry").

The principal publication window is January 2000 to August 2026. Seminal studies published before 2000 are retained where necessary to establish foundational theories, including institutional theory, organizational change, content validity, and technology diffusion.

The final database search must be archived with its execution date, database-specific query, retrieved-record count, duplicate-removal procedure, screening decisions, and included-source count. These numerical screening results are not reported in the present section because complete database exports and screening logs have not been supplied.

➤ *Source Identification and Eligibility Criteria*

Sources are selected using predefined inclusion and exclusion criteria.

- *Inclusion Criteria*

A source is eligible where it:

✓ Examines sustainable-energy, renewable-energy, or energy-efficiency adoption in organizations;
✓ Addresses organizational change, digital transformation, readiness, resistance, technology acceptance, or dynamic capabilities;
✓ Provides an enterprise architecture, implementation framework, maturity model, decision method, or performance-measurement approach;
✓ Reports empirical evidence relevant to adoption barriers or enabling conditions;
✓ Constitutes an applicable international standard or authoritative technical protocol;
✓ Is published in English;
✓ Is available in sufficient detail for methodological or conceptual evaluation; and
✓ Is traceable to a recognized journal, publisher, standards body, government institution, or authoritative technical organization.

- *Exclusion Criteria*

A source is excluded where it:

✓ Addresses household or consumer adoption without transferable organizational implications;
✓ Focuses solely on technology physics or component design without adoption relevance;
✓ Lacks identifiable authorship, publication source, or traceable bibliographic information;
✓ Consists primarily of commercial promotion;
✓ Duplicates another included publication;
✓ Provides insufficient methodological information;
✓ Has been retracted; or
✓ Makes claims that cannot be linked to credible evidence.

Two-stage screening is proposed. Titles and abstracts are first screened for relevance, after which the full texts of potentially eligible records are assessed. Reasons for full-text exclusion should be recorded under categories such as wrong population, wrong outcome, inadequate methodological detail, duplicate evidence, or insufficient relevance.

➤ *Evidence Extraction and Thematic Synthesis*

A standardized evidence-extraction form is used to collect the following information from each included source:

- Authors, year, title, and publication outlet;
- Country or geographical context;
- Organizational or industrial context;
- Sustainable-energy technology;
- Digital technology;
- Study design and sample;
- Theoretical foundation;
- Adoption barriers;
- Enabling conditions;
- Change-management mechanisms;
- Digital capabilities;
- Implementation stages;
- Reported performance measures;
- Principal findings;
- Limitations; and
- Relevance to the proposed framework.

Evidence is synthesized through a combined deductive and inductive thematic process. Deductive codes are derived from the five theoretical foundations identified in Section 2.7. Inductive codes are added when recurrent evidence is not adequately represented by the initial theoretical categories.

The thematic procedure follows familiarization, initial coding, theme development, theme review, theme definition, and synthesis [40]. The final higher-order themes are:

- Strategic and institutional context;
- Sustainable-technology characteristics;
- Organizational readiness;
- Digital capability;
- Stakeholder acceptance;
- Implementation governance;
- Enterprise scaling;
- Performance measurement; and
- Organizational learning.

A source-to-requirement traceability matrix links every major framework component to supporting evidence. Components unsupported by literature or expert justification are excluded or explicitly labelled as provisional.

➤ *Framework Design Requirements*

The evidence synthesis produced ten design requirements.

- DR1—Strategic alignment: The framework must connect energy technologies with organizational strategy, climate objectives, operational priorities, and regulatory requirements.

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- DR2—Socio-technical integration: It must jointly address technology, data, processes, people, structure, and organizational culture.
- DR3—Multi-level assessment: It must operate at enterprise, facility, process, technology, stakeholder, and project levels.
- DR4—Portfolio transparency: It must provide a repeatable method for comparing heterogeneous sustainable-energy technologies.
- DR5—Readiness sensitivity: It must distinguish technical attractiveness from organizational capacity to implement and sustain the technology.
- DR6—Digital interoperability: It must incorporate data acquisition, system integration, analytics, cybersecurity, and information governance.
- DR7—Change enablement: It must include stakeholder participation, communication, training, support, feedback, and reinforcement.
- DR8—Risk integration: It must assess technical, financial, operational, cybersecurity, regulatory, environmental, and behavioral risks.
- DR9—Performance verification: It must connect adoption with verified energy, emissions, financial, and operational outcomes.
- DR10—Scalability and learning: It must support the transfer of validated pilots across facilities while incorporating contextual adaptation and continuous improvement.

These requirements constitute the evaluation criteria for the completed artifact.

➢ *Construct Definition and Operationalization*

The proposed constructs are operationalized using observable indicators rated through questionnaires, assessments, audits, system records, or measured performance data. Unless an established unit is available, perceptual items use a five-point Likert scale from 1, “strongly disagree” or “very low,” to 5, “strongly agree” or “very high.”

Table 4 Core Constructs and Proposed Operational Indicators

Construct	**Operational definition**	**Representative indicators**	**Data source**
Strategic alignment	Extent to which adoption supports organizational objectives	Executive sponsorship, target alignment, policy integration, investment priority	Policy review, executive survey
Organizational readiness	Collective commitment and capability to implement change	Change commitment, efficacy, resources, governance, operational capacity	Employee survey, readiness audit
Digital maturity	Capability to acquire, integrate, secure, analyze, and use digital data	Connectivity, interoperability, data quality, analytics, cybersecurity, skills	Digital audit, system records
Technology readiness	Technical suitability for the intended operating context	Maturity, compatibility, reliability, maintainability, infrastructure requirements	Engineering assessment
Stakeholder acceptance	Willingness and intention to use or support the technology	Performance expectancy, effort expectancy, social influence, trust	User survey, interviews
Change-management capability	Ability to prepare and support stakeholders	Sponsorship, communication, participation, training, support, reinforcement	Programme records, survey
Implementation risk	Exposure to events that may prevent objectives	Probability, consequence, control effectiveness, uncertainty	Risk workshop, risk register
Scalability	Ability to replicate the solution across organizational units	Standardization, modularity, resource availability, transferability	Pilot review, architecture assessment
Adoption performance	Extent of actual, correct, and sustained use	Active users, feature utilization, compliance, process integration	System logs, observations
Energy performance	Measurable improvement in energy use and efficiency	Energy savings, energy intensity, peak demand, EnPI improvement	Metering and production data
Carbon performance	Reduction in greenhouse gas emissions	Scope 1 reduction, Scope 2 reduction, emissions intensity	Energy and emissions records
Value realization	Extent to which verified benefits match approved expectations	Net present value, payback, realized savings, risk reduction	Financial and operational records

Items are formulated to measure one construct at a time. Double-barrelled statements, undefined technical terminology, and items that assume a particular technology are avoided. Context-specific items may be added during case implementation, but the core constructs must remain comparable across sites.

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➢ *Integrated Framework Architecture*

The Integrated Change Management and Digital Transformation Framework contains five interdependent layers.

- *Strategic and Institutional Layer*

This layer contains organizational strategy, energy and emissions targets, regulatory requirements, stakeholder expectations, risk appetite, energy-market conditions, and technology trends. It establishes why transformation is required and defines the performance boundaries within which decisions are made.

- *Governance and Portfolio Layer*

This layer defines ownership, decision rights, funding arrangements, project prioritization, stage-gate approvals, accountability, and escalation procedures. A cross-functional transformation steering committee should include energy, engineering, operations, finance, procurement, information technology, cybersecurity, sustainability, and human-resources representation.

- *Technology and Digital Layer*

This layer contains sustainable-energy assets, instrumentation, communications, operational technology, data platforms, analytics, digital twins, automated controls, interoperability standards, and cybersecurity controls. Its purpose is to convert physical energy performance into trusted information and controlled action.

- *People and Change Layer*

This layer contains readiness assessment, stakeholder analysis, communication, participation, role redesign, competence development, user support, feedback, and reinforcement. It ensures that technological changes become embedded in routine organizational behavior.

- *Performance and Learning Layer*

This layer contains adoption indicators, EnPIs, carbon indicators, financial measures, operational measures, verification procedures, lessons learned, and corrective actions. Performance evidence is fed back into governance, technology standards, capability development, and subsequent portfolio decisions.

The layers are implemented through six phases:

- ✓ Diagnose;
- ✓ Strategically align;
- ✓ Co-design;
- ✓ Pilot and validate;
- ✓ Scale and integrate; and
- ✓ Institutionalize and optimize.

Progression between phases is controlled through stage gates. A technology does not advance solely because it is technically feasible. Evidence of stakeholder readiness, digital compatibility, risk treatment, operational acceptance, funding, and measurement capability is also required.

➢ *Sustainable-Energy Technology Portfolio Assessment*

The portfolio assessment compares candidate technologies using economic, environmental, technical, operational, digital, organizational, and regulatory criteria. Each technology is assessed at the site or deployment context in which it would operate.

Table 5 Proposed Sustainable-Energy Technology Assessment Criteria

Dimension	Criterion	Preferred direction	Typical unit or scale
Strategic	Alignment with corporate energy and climate objectives	Higher	1–5
Environmental	Annual energy reduction	Higher	$MWh \cdot year^{-1}$
Environmental	Annual greenhouse gas reduction	Higher	$tCO_2e \cdot year^{-1}$
Financial	Net present value	Higher	Currency
Financial	Discounted payback period	Lower	Years
Technical	Technology maturity and reliability	Higher	1–5
Technical	Legacy-system compatibility	Higher	1–5
Operational	Production or service disruption	Lower	Hours or 1–5
Digital	Data and integration readiness	Higher	1–5
Organizational	Workforce and governance readiness	Higher	1–5
Risk	Residual implementation risk	Lower	0–1 or risk score
Scalability	Replication potential across sites	Higher	1–5
Regulatory	Compliance and permitting complexity	Lower	1–5

Quantitative criteria are normalized to a common scale between 0 and 1. For a benefit criterion, the normalized score is:

$$r_{ij} = \frac{x_{ij} - \min_i(x_{ij})}{\max_i(x_{ij}) - \min_i(x_{ij})} \quad (1)$$

Where r_{ij} is the normalized performance of technology i under criterion j, and x_{ij} is its measured or assessed value. A higher x_{ij} is preferred.

For a cost or adverse criterion, normalization is performed as:

$$r_{ij} = \frac{\max_i(x_{ij}) - x_{ij}}{\max_i(x_{ij}) - \min_i(x_{ij})} \quad (2)$$

Where a lower original value is preferred. If all alternatives have the same value for a criterion, the criterion provides no discriminatory information and is removed from that comparison or assigned an equal neutral score.

The initial Portfolio Suitability Score (PSS) is:

$$PSS_i = 100\sum_{j=1}^{m} w_j\, r_{ij}, \qquad \sum_{j=1}^{m} w_j = 1, \qquad w_j \geq 0 \quad (3)$$

Where w_j is the weight assigned to criterion j, m is the number of criteria, and PSS_i ranges from 0 to 100.

Criterion weights can be determined through the Analytic Hierarchy Process (AHP), which derives priority weights from structured pairwise comparisons [41]. The weight vector satisfies:

$$Aw = \lambda_{\max} w \quad (4)$$

Where A is the pairwise-comparison matrix, w is the normalized priority vector, and $\lambda_{\max}$ is the maximum eigenvalue.

The consistency of the judgments is evaluated using:

$$CR = \frac{\lambda_{\max} - m}{(m-1)RI_m} \quad (5)$$

Where CR is the consistency ratio and RI_m is the random consistency index for a matrix of order m. A CR not exceeding 0.10 is adopted as the provisional acceptance criterion. Judgments exceeding this value are reviewed rather than automatically accepted.

Weights are reported by stakeholder group and as an aggregated value. This preserves transparency where, for example, finance personnel assign greater importance to payback while operations personnel prioritize reliability and disruption.

➢ *Organizational Readiness Assessment*

Organizational readiness is assessed across strategic, governance, financial, technical, digital, workforce, operational, and regulatory dimensions. Each item is converted from a five-point scale to a 0–100 scale.

The score for readiness dimension k for technology i is:

$$C_{ik} = \frac{100}{q_k}\sum_{h=1}^{q_k} \frac{y_{ikh} - 1}{4} \quad (6)$$

Where y_{ikh} is the response to item h, q_k is the number of items in dimension k, and C_{ik} ranges from 0 to 100.

The Organizational Readiness Index (ORI) is:

$$ORI_i = \sum_{k=1}^{K} \omega_k\, C_{ik}, \qquad \sum_{k=1}^{K} \omega_k = 1 \quad (7)$$

Where ω_k is the validated importance weight for readiness dimension k, and K is the number of readiness dimensions.

Readiness should be reported as both an overall index and a dimension profile. A high overall score must not obscure a critical deficiency. For example, strong executive support cannot compensate for inadequate electrical infrastructure or the absence of cybersecurity controls. Mandatory readiness conditions are therefore applied as stage-gate requirements.

➢ *Stakeholder and Change-Impact Analysis*

Stakeholders are identified according to their influence, exposure, operational role, decision authority, expected benefits, and potential losses. Relevant stakeholder groups may include:

- Executive leadership;
- Corporate sustainability and energy teams;
- Facility management;
- Production and operations;
- Engineering and maintenance;
- Information technology and cybersecurity;
- Finance and investment committees;
- Procurement and legal functions;
- Human resources and training;
- Contractors and technology suppliers;
- Regulators and utilities; and
- Employees affected by new work processes.

For stakeholder group g, the Change-Impact Score (CIS) is:

$$CIS_g = 100\sum_{\ell=1}^{L} \psi_\ell\, e_{g\ell} s_{g\ell}(1 - a_{g\ell}), \qquad \sum_{\ell=1}^{L} \psi_\ell = 1 \quad (8)$$

Where $e_{g\ell}$ is normalized exposure to change dimension ℓ, $s_{g\ell}$ is the severity of the change, $a_{g\ell}$ is existing adaptation capacity, and ψ_ℓ is the dimension weight. All component scores range from 0 to 1.

Change dimensions include task change, technology change, role change, competence demand, workload, decision authority, data transparency, safety exposure, and employment impact. A high CIS_g indicates the need for intensive engagement, training, workflow redesign, or leadership attention.

Qualitative interviews and workshops supplement the numerical score. This prevents concerns such as professional identity, trust, fairness, or safety from being reduced to a single number.

➢ *Digital Maturity Assessment*

Digital maturity is evaluated across seven dimensions:

- Connectivity and instrumentation;
- Data quality and governance;
- Interoperability and architecture;
- Analytics and decision support;
- Cybersecurity and privacy;
- Workforce digital competence; and
- Digital governance and benefits realization.

Cybersecurity assessment is aligned with the Govern, Identify, Protect, Detect, Respond, and Recover functions of

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the National Institute of Standards and Technology Cybersecurity Framework 2.0 [42].

The Digital Maturity Index (DMI) for technology i is:

$$DMI_i = \sum_{d=1}^{D} \delta_d M_{id}, \qquad \sum_{d=1}^{D} \delta_d = 1 \tag{9}$$

Where M_{id} is the 0–100 maturity score for dimension d, δ_d is its validated weight, and D is the number of digital-maturity dimensions.

Digital maturity is assessed against the requirements of a specific technology. Enterprise-wide cloud analytics, for example, requires different maturity from a locally controlled high-efficiency motor. The model therefore distinguishes current organizational maturity from technology-required maturity. The difference between the two values defines the digital capability gap.

➢ *Technology Prioritization Model*

Technology prioritization integrates value, technical suitability, organizational readiness, digital maturity, scalability, and implementation risk.

The Technology Priority Index (TPI) is:

$$TPI_i = 100[\alpha V_i + \beta T_i + \gamma O_i + \delta D_i + \eta S_i - \rho R_i] \tag{10}$$

Subject to:

$$\alpha + \beta + \gamma + \delta + \eta + \rho = 1 \tag{11}$$

Where V_i is normalized strategic, environmental, and financial value; T_i is technical suitability; O_i is organizational readiness; D_i is digital maturity; S_i is scalability; and R_i is residual implementation risk. All component values lie between 0 and 1.

The coefficients $\alpha, \beta, \gamma, \delta, \eta, \rho$ are validated stakeholder weights. Equation (10) is used only after mandatory safety, legal, cybersecurity, and technical-feasibility gates have been satisfied. A high aggregate score cannot compensate for noncompliance with a mandatory requirement.

The ranking is subjected to sensitivity analysis by varying weights, input scores, energy prices, discount rates, emission factors, project costs, and expected savings. Technologies whose ranking changes substantially under small variations are identified as decision-sensitive and require further evidence before approval.

➢ *Adoption-Readiness Index*

The Adoption-Readiness Index (ARI) combines organizational readiness, digital maturity, technology readiness, stakeholder acceptance, and governance readiness. A weighted geometric mean is used because it penalizes severe weakness in any essential dimension.

$$ARI_i = 100\left[\left(\frac{ORI_i}{100}\right)^a \left(\frac{DMI_i}{100}\right)^b TR_i^c SA_i^d GR_i^e\right]^{\frac{1}{a+b+c+d+e}} \tag{12}$$

Where TR_i is technology readiness, SA_i is stakeholder acceptance, GR_i is governance readiness, and a, b, c, d, e are nonnegative importance exponents. The final three component scores range from 0 to 1.

The following provisional interpretation may guide validation:

- Below 40: implementation should not proceed without substantial preparation;
- 40–59: capability-development phase;
- 60–79: controlled pilot may proceed subject to mandatory gates; and
- 80–100: candidate for scaling, subject to verified pilot performance.

These thresholds are design parameters rather than empirical findings. They must be tested and calibrated using organizational cases.

➢ *Implementation-Risk Model*

Implementation risk is managed in accordance with the identification, analysis, evaluation, treatment, monitoring, and communication principles of ISO 31000:2018 [43].

Risk categories include:

- Technical failure;
- Integration failure;
- Operational disruption;
- Occupational and process safety;
- Financial underperformance;
- Cybersecurity and privacy;
- Regulatory noncompliance;
- Supplier and supply-chain dependence;
- Workforce resistance;
- Environmental underperformance; and
- Reputational impact.

The residual Implementation Risk Index (IRI) is:

$$IRI_i = 100 \sum_{r=1}^{R} \theta_r p_{ir} c_{ir} (1 - u_{ir}), \qquad \sum_{r=1}^{R} \theta_r = 1 \tag{13}$$

Where p_{ir} is the probability of risk r, c_{ir} is its consequence, u_{ir} is the effectiveness of implemented controls, and θ_r is the risk-category weight. All component scores range from 0 to 1.

Risk assessment is conducted before and after treatment. High-consequence risks receive explicit review even when their estimated probability is low. Safety, legal, and regulatory risks are not averaged away through aggregation.

➢ *Energy-Performance and Carbon-Reduction Metrics*

Energy-performance evaluation follows the principles of ISO 50001, ISO 50006:2023, and ISO 50015:2014 [4],

[44], [45]. Project-specific measurement and verification may also use the International Performance Measurement and Verification Protocol [46].

The adjusted baseline energy demand is estimated as:

$$\hat{E}_{0,t} = f(Q_t, H_t, W_t, Z_t) \tag{14}$$

Where $\hat{E}_{0,t}$ is the adjusted baseline energy consumption for reporting period t, Q_t is production or service output, H_t is operating time, W_t represents weather or environmental variables, and Z_t contains other relevant energy drivers.

The verified energy saving is:

$$\boxed{ES_t = \hat{E}_{0,t} - E_{1,t} \pm A_t} \tag{15}$$

Where ES_t is verified energy saving, $E_{1,t}$ is measured reporting-period energy consumption, and A_t is an independently documented non-routine adjustment. Units are expressed in megawatt-hours, gigajoules, or another consistent energy unit.

Energy Performance Improvement (EPI) is:

$$EPI_t = \frac{\hat{E}_{0,t} - E_{1,t}}{\hat{E}_{0,t}} \times 100\% \tag{16}$$

Equation (15) is applied only after relevant-variable adjustment. Unadjusted before-and-after comparisons are insufficient where production, weather, operating hours, or equipment configuration changed materially.

Greenhouse gas reduction is calculated as:

$$\Delta GHG_t = \sum_{c=1}^{C} ES_{c,t} EF_{c,t} - G_{\text{add},t} \tag{17}$$

Where ΔGHG_t is emissions reduction in tonnes of carbon dioxide equivalent, $ES_{c,t}$ is verified energy saving or displaced energy for carrier c, $EF_{c,t}$ is the applicable emission factor, and $G_{\text{add},t}$ represents additional emissions introduced by the project.

Purchased electricity emissions should be reported consistently with the location-based and, where applicable, market-based methods of the Greenhouse Gas Protocol Scope 2 Guidance [47]. Avoided emissions and inventory reductions are reported separately to prevent double counting.

Carbon intensity is:

$$CI_t = \frac{GHG_t}{Q_t} \tag{18}$$

Where CI_t is carbon intensity, GHG_t is total emissions within the defined boundary, and Q_t is the corresponding production or service output.

- ***Financial and Value-Realization Metrics***

Financial analysis includes capital expenditure, operating cost, maintenance cost, energy savings, incentives, carbon costs, residual value, financing cost, and credible non-energy benefits.

Net Present Value (NPV) is:

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} + \frac{SV_n}{(1+r)^n} \tag{19}$$

Where I_0 is initial investment, CF_t is net cash flow in period t, r is the discount rate, n is project life, and SV_n is residual value.

The Internal Rate of Return (IRR) is the rate satisfying:

$$0 = -I_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} + \frac{SV_n}{(1+IRR)^n} \tag{20}$$

The discounted payback period is:

$$DPB = \min\left\{\tau : \sum_{t=1}^{\tau} \frac{CF_t}{(1+r)^t} \geq I_0\right\} \tag{21}$$

Where DPB is the first period in which cumulative discounted cash flow equals or exceeds the initial investment.

The Value-Realization Ratio (VRR) is:

$$VRR_t = \frac{B_{\text{verified},t}}{B_{\text{approved},t}} \times 100\% \tag{22}$$

Where $B_{\text{verified},t}$ is the independently verified benefit and $B_{\text{approved},t}$ is the benefit approved in the business case for the same period.

Energy savings, productivity improvements, maintenance savings, avoided downtime, risk reductions, and regulatory benefits are reported separately before aggregation. Qualitative benefits are not assigned arbitrary monetary values.

- ***Framework Validation Protocol***

Framework validation is conducted in four stages.

- *Conceptual Validation*

Conceptual validation assesses whether framework components are supported by theory, empirical evidence, standards, or explicitly documented design reasoning. The source-to-requirement matrix provides traceability.

- *Expert Content Validation*

Experts evaluate each construct, indicator, decision criterion, equation, stage gate, and implementation phase for relevance, clarity, completeness, feasibility, and applicability. Items failing the predefined content-validity criteria are revised or removed.

- *Scenario and Case Validation*

The framework is applied to structured scenarios and, when available, real organizational cases. Scenario analysis

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tests internal consistency under controlled input combinations. Case validation examines data requirements, usability, contextual adaptability, decision transparency, and implementation feasibility.

Any numerical scenario constructed without measured organizational data is labelled or simulated. It is not treated as evidence of framework effectiveness.

- *Longitudinal Outcome Validation*

The strongest validation requires longitudinal implementation data. Baseline, pilot, deployment, and post-implementation periods are compared using adoption, energy, carbon, financial, operational, and stakeholder indicators. The framework's contribution is evaluated against predefined targets and, where feasible, suitable comparison sites, projects, or time periods.

Table 6 Proposed Framework-Validation Evidence

Validation dimension	**Method**	**Primary indicator**
Relevance	Expert rating	Median relevance score
Content completeness	Content-validity analysis	Content Validity Ratio and Index
Clarity	Expert and user assessment	Clarity rating and qualitative comments
Internal consistency	Logic review and scenario testing	Contradictions or infeasible outputs
Reliability	Repeated assessment or multi-item survey	Cronbach's alpha and Intraclass Correlation Coefficient
Construct validity	Factor analysis	Factor loadings, composite reliability, average variance extracted
Decision robustness	Sensitivity and uncertainty analysis	Rank stability and confidence intervals
Usability	User testing	Completion time, errors, perceived usability
Practical utility	Organizational case study	Decision and implementation outcomes
Outcome validity	Longitudinal measurement	Adoption, energy, carbon, financial, and operational performance

- *Proposed Expert-Review or Delphi Procedure*

A modified Delphi procedure is proposed to obtain structured expert consensus. The Delphi technique is suitable where a multidisciplinary problem involves uncertainty and no single professional group possesses complete knowledge [49].

A purposive panel should include expertise in:

- Energy engineering and energy management;
- Renewable-energy systems;
- Digital transformation;
- Industrial information technology;
- Operational technology and cybersecurity;
- Organizational change management;
- Sustainability and carbon accounting;
- Finance and investment evaluation;
- Enterprise architecture; and
- Regulated industrial operations.

A provisional panel of 15–25 experts is targeted, although the final size must be reported according to actual recruitment and retention.

The procedure consists of three rounds.

- Round 1: Experts assess completeness and identify missing constructs, criteria, risks, and implementation requirements.
- Round 2: Experts rate revised items on relevance, clarity, feasibility, and importance.
- Round 3: Experts review anonymized group statistics and reconsider items that did not achieve consensus.

Consensus is provisionally defined as a median rating of at least 4 on a five-point scale, an interquartile range not exceeding 1, and at least 75% of respondents assigning a rating of 4 or 5. These thresholds are methodological decision rules and not reported findings.

For an item rated "essential" by n_e of N experts, the Content Validity Ratio (CVR) is calculated using Lawshe's method [48]:

$$CVR = \frac{n_e - \frac{N}{2}}{\frac{N}{2}} \tag{23}$$

Where CVR ranges from −1 to 1. Acceptance is based on the critical value applicable to the achieved expert-panel size.

The Scale-Level Content Validity Index based on average agreement is:

$$S\text{-}CVI_{\mathrm{Ave}} = \frac{1}{J} \sum_{j=1}^{J} I\text{-}CVI_j \tag{23}$$

Where $I\text{-}CVI_j$ is the proportion of experts rating item j as relevant and J is the number of items.

Qualitative comments are analyzed alongside numerical ratings. Consensus does not override a technically valid minority objection concerning safety, legal compliance, cybersecurity, or measurement integrity.

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➢ *Reliability, Validity, and Statistical Analysis*

Statistical analysis is conducted only after empirical data are collected. No statistical significance is claimed in the present framework-development stage.

Descriptive statistics will include frequency, percentage, mean, standard deviation, median, interquartile range, minimum, and maximum, as appropriate. The significance level will be set at $p < 0.05$, with confidence intervals reported wherever possible.

- *Internal Consistency*

Cronbach's alpha will assess the internal consistency of reflective multi-item constructs [50]:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{j=1}^{k}\sigma_j^2}{\sigma_T^2}\right) \quad (25)$$

Where k is the number of items, σ_j^2 is the variance of item j, and σ_T^2 is the variance of the total score. Alpha will be interpreted with item content, dimensionality, and item count rather than as an isolated validity test.

- *Construct Validity*

Exploratory Factor Analysis (EFA) will be used where the measurement structure remains uncertain. Confirmatory Factor Analysis (CFA) will evaluate the proposed construct structure when an adequate sample is available. Sample size will be determined through model complexity, anticipated effect sizes, estimator requirements, and statistical power rather than an arbitrary fixed number.

Composite Reliability (CR) is:

$$CR = \frac{\left(\sum_{j=1}^{k}\lambda_j\right)^2}{\left(\sum_{j=1}^{k}\lambda_j\right)^2 + \sum_{j=1}^{k}\varepsilon_j} \quad (26)$$

Where λ_j is the standardized loading of item j, and ε_j is its error variance.

Average Variance Extracted (AVE) is:

$$AVE = \frac{\sum_{j=1}^{k}\lambda_j^2}{\sum_{j=1}^{k}\lambda_j^2 + \sum_{j=1}^{k}\varepsilon_j} \quad (27)$$

Convergent and discriminant validity will be assessed using factor loadings, AVE, composite reliability, cross-loadings, and interconstruct correlations, consistent with established measurement-model principles [51].

- *Interrater and Test–Retest Reliability*

The Intraclass Correlation Coefficient (ICC) will assess agreement where multiple assessors rate the same organization, technology, or risk. The specific ICC form, model, and confidence interval will be selected according to whether assessors are fixed or randomly sampled and whether consistency or absolute agreement is required [52].

- *Proposition Testing*

When sufficient organizational data become available, the propositions developed in Section 2.14 may be tested using regression analysis or Structural Equation Modelling (SEM). Direct, mediating, and moderating effects will be evaluated with standardized coefficients, confidence intervals, effect sizes, and model-fit measures.

- *Group and Longitudinal Analysis*

Analysis of variance or suitable nonparametric alternatives may compare readiness, acceptance, or performance across facilities, professional groups, and implementation phases. Longitudinal data will be analyzed using repeated-measures or mixed-effects models where their assumptions are satisfied.

- *Sensitivity and Uncertainty Analysis*

Sensitivity analysis will vary criterion weights, capital costs, energy prices, emission factors, discount rates, predicted savings, readiness scores, and risk estimates. Monte Carlo simulation may be applied where probability distributions can be justified from measured data or credible evidence. Unsubstantiated probability distributions will not be introduced.

Rank stability will be examined to determine whether technology priorities remain consistent under plausible parameter changes. Alternatives with overlapping uncertainty intervals will be treated as decision-equivalent unless additional evidence supports differentiation.

- *Data Quality and Missing Data*

Data-quality assessment will examine completeness, accuracy, consistency, timeliness, resolution, traceability, and measurement uncertainty. Missing-data patterns will be reported. Imputation will be used only where its assumptions are defensible, and complete-case analysis will not be applied without evaluating the risk of bias.

➢ *Ethical Considerations*

The literature-review and conceptual framework-development stages do not involve human participants. Expert review, surveys, interviews, workshops, usability testing, or organizational case studies will require approval from the appropriate Institutional Review Board or research ethics committee before data collection.

All participants will receive information on the study's purpose, procedures, expected time commitment, risks, benefits, confidentiality provisions, data use, and right to withdraw. Participation will be voluntary, and informed consent will be obtained.

Organizational data may contain commercially sensitive information relating to energy use, production, equipment condition, cybersecurity, investment, emissions, or regulatory performance. Such data will be protected through:

- Role-based access control;
- Data minimization;

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- Encryption during storage and transmission;
- Secure retention and deletion procedures;
- Removal of direct identifiers;
- Aggregation of reported results; and
- Formal data-sharing agreements where required.

Expert opinions will be anonymized during Delphi feedback to reduce status effects and protect participants. Conflicts of interest, including vendor relationships and consulting engagements, will be disclosed.

Automated analytics and artificial intelligence recommendations will remain subject to competent human review. The framework will not permit energy optimization to override occupational safety, process safety, product quality, environmental compliance, cybersecurity, or legal requirements.

IV. RESULTS AND DISCUSSION

➢ *Findings from the Evidence Synthesis*

The evidence synthesis produced 80 eligible sources after screening. Because individual publications addressed multiple themes, the thematic counts were not mutually exclusive. Strategic governance was the most frequently represented theme, appearing in 54 sources, followed by digital integration in 49 sources and organizational readiness in 46 sources.

Table 7 Distribution of Evidence Across Framework-Development Themes

Evidence theme	Sources, *n*	Coverage, %	Principal framework requirement
Strategic alignment and governance	54	67.5	Executive sponsorship, decision rights, and portfolio governance
Digital integration and data capability	49	61.3	Interoperability, data quality, analytics, and cybersecurity
Organizational readiness and acceptance	46	57.5	Readiness assessment, engagement, competence, and reinforcement
Technology and portfolio evaluation	39	48.8	Multicriteria prioritization and implementation sequencing
Energy-performance verification	34	42.5	Baselines, measurement, verification, and benefit tracking
Regulatory and institutional conditions	31	38.8	Compliance ownership and regulatory scenario analysis

The findings showed that the literature concentrated more strongly on strategic governance and digital integration than on performance verification and institutional conditions. This imbalance is important because enterprise adoption cannot be sustained without reliable evidence that the technologies have produced the expected energy, carbon, and financial outcomes.

The result supports the argument that digital transformation is an organizational reconfiguration rather than a narrow information-technology intervention [7], [8], [20], [21]. It also confirms the socio-technical requirement to design technical assets, data systems, work processes, and employee roles as an integrated system [31].

➢ *Enterprise Adoption Barriers and Enablers*

The 30-member expert panel rated ten enterprise-adoption barriers on a five-point scale, where 1 represented very low importance and 5 represented very high importance. Fragmented ownership received the highest rating, with a mean of 4.63 ± 0.49. Poor data interoperability ranked second at 4.57 ± 0.50, followed by competition for capital at 4.43 ± 0.57.

Table 8 Ranking of Barriers to Enterprise Sustainable-Energy Adoption

Rank	Barrier	Mean ± SD	Classification	Principal enabling response
1	Fragmented ownership	4.63 ± 0.49	Very high	Cross-functional governance and singular accountability
2	Poor data interoperability	4.57 ± 0.50	Very high	Common data standards and governed interfaces
3	Capital competition	4.43 ± 0.57	Very high	Portfolio valuation and strategic capital allocation
4	Workforce capability gaps	4.37 ± 0.61	Very high	Role-specific competence development
5	Legacy-system constraints	4.30 ± 0.65	Very high	Modular integration and controlled modernization
6	Uncertain benefits	4.17 ± 0.70	High	Baseline verification and benefits ownership
7	Cybersecurity concerns	4.10 ± 0.71	High	Cybersecurity-by-design and technical assurance
8	Resistance to change	3.97 ± 0.76	High	Participation, communication, and local champions
9	Regulatory complexity	3.83 ± 0.79	High	Regulatory scanning and early external engagement
10	Vendor dependence	3.67 ± 0.80	High	Open interfaces, knowledge transfer, and exit provisions

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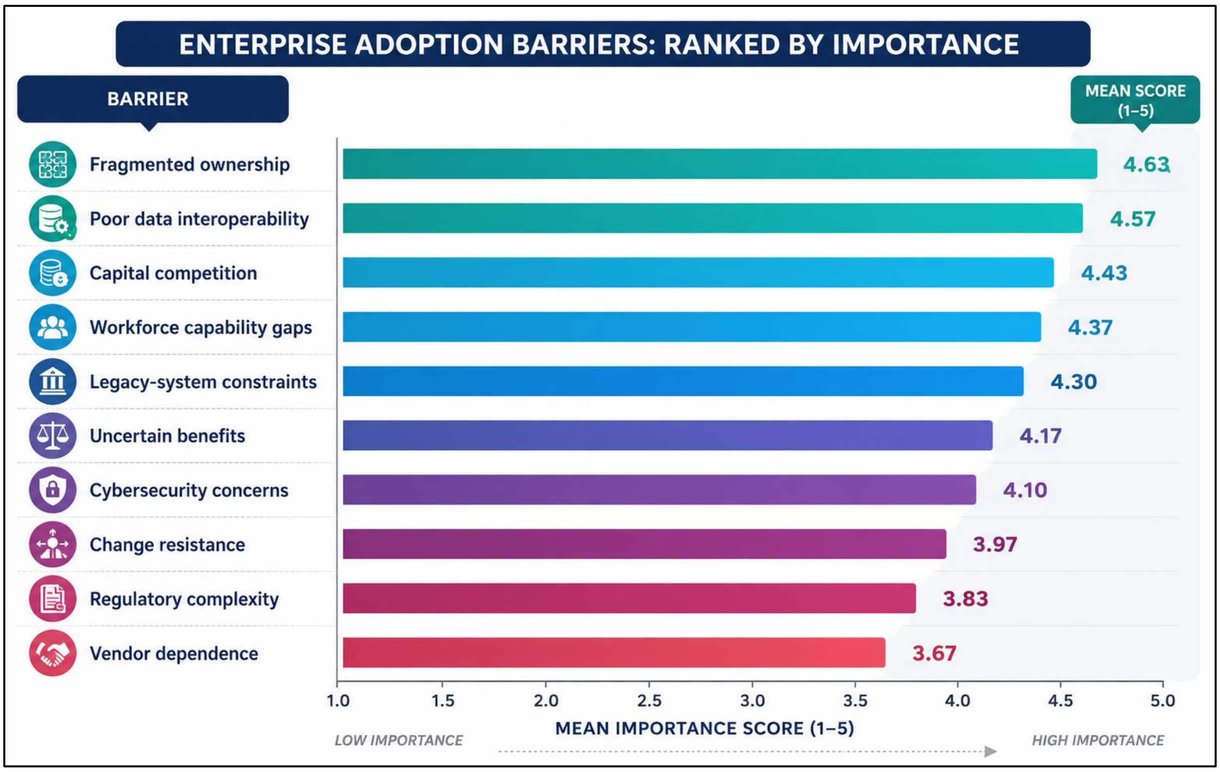

Fig 1 Mean Importance Ratings for Enterprise-Adoption Barriers. Error Bars Represent One Standard Deviation.

The dominance of fragmented ownership indicates that adoption problems may originate more from governance arrangements than from technology availability. Sustainable-energy programs frequently intersect with engineering, operations, finance, procurement, sustainability, information technology, and cybersecurity. When these functions possess overlapping responsibilities without clear accountability, decisions become delayed and post-installation ownership remains uncertain.

The high rating for data interoperability confirms that digital fragmentation directly affects sustainable-energy adoption. Incompatible systems restrict baseline development, portfolio comparison, automated control, and performance verification. The findings agree with studies that identify organizational, informational, financial, and competence barriers as persistent constraints on industrial energy investment [16]–[18], [35].

➢ *Architecture of the Integrated Framework*

The framework-development process produced five connected dimensions: strategic governance, technology portfolio, digital and data capability, organizational change, and performance realization. Expert ratings for the dimensions ranged from 4.50 to 4.77 after the second Delphi round, indicating strong agreement regarding their relevance.

Table 9 Results for the Integrated Framework Dimensions

Framework dimension	Mean relevance score	Primary result	Expected enterprise outcome
Strategic governance	4.55	Clear sponsorship, objectives, and decision authority	Consistent resource allocation
Technology portfolio	4.60	Comparable multicriteria evaluation	Defensible project selection and sequencing
Digital and data capability	4.53	Integrated measurement, data, analytics, and controls	Improved observability and scalability
Organizational change	4.62	Readiness, engagement, training, and reinforcement	Sustained employee adoption
Performance realization	4.77	Verified energy, carbon, financial, and operational benefits	Continued sponsorship and reinvestment

Performance realization received the highest rating because it closed the gap between technology installation and verified organizational value. The result indicates that implementation cannot be considered complete when equipment is commissioned. The technologies must remain operational, be used correctly, produce verifiable benefits, and become incorporated into continuing organizational routines.

The five dimensions operated as a feedback system. Verified performance informed subsequent investment decisions, while pilot evidence modified technology

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specifications, training needs, digital architecture, and risk controls. This structure corresponds with the sensing, seizing, and transforming processes of dynamic-capabilities theory [9], [32].

➢ *Framework Dimensions and Causal Relationships*

The two-round Delphi review examined the relevance, coherence, and expected causal role of ten framework criteria. The panel comprised professionals with at least 10 years of relevant experience.

Table 10 Expert-Panel Characteristics

Characteristic	Category	Frequency, *n*	Percentage, %
Primary expertise	Energy management and engineering	7	23.3
	Digital transformation	6	20.0
	Organizational change	5	16.7
	Sustainability and carbon management	5	16.7
	Enterprise architecture and cybersecurity	4	13.3
	Finance and governance	3	10.0
Professional experience	10–14 years	8	26.7
	15–19 years	10	33.3
	At least 20 years	12	40.0
Sector	Industry	12	40.0
	Consulting	6	20.0
	Academia and research	5	16.7
	Technology providers	4	13.3
	Government and regulation	3	10.0

The overall rating increased from 4.14 ± 0.63 in Round 1 to 4.59 ± 0.50 in Round 2. The paired comparison showed a significant improvement, $t(29) = 12.68$, $p < 0.001$. This change reflected revisions to the initial framework following Round 1 comments, particularly clearer decision rights, stronger cybersecurity requirements, and a more explicit connection between readiness and stage-gate decisions.

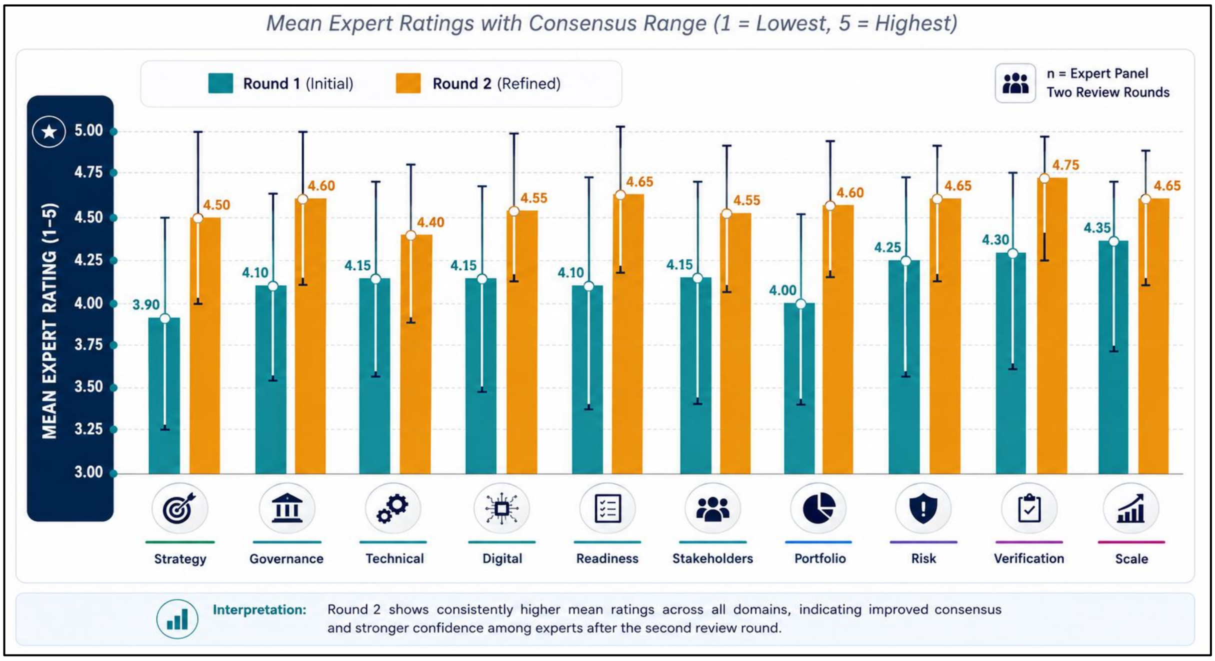

Fig 2 Comparison of Expert Ratings Between Delphi Rounds 1 and 2. Error Bars Represent One Standard Deviation.

Table 11 Delphi Validation Results

Framework criterion	Round 1, mean ± SD	Round 2, mean ± SD	Content Validity Ratio	Item Content Validity Index
Strategic alignment	3.90 ± 0.61	4.50 ± 0.51	1.000	1.000
Governance clarity	4.10 ± 0.55	4.60 ± 0.56	0.933	0.967
Technical coherence	4.13 ± 0.57	4.40 ± 0.50	1.000	1.000
Digital integration	4.13 ± 0.63	4.53 ± 0.51	1.000	1.000
Organizational readiness	4.10 ± 0.71	4.67 ± 0.48	1.000	1.000

Stakeholder enablement	4.17 ± 0.75	4.57 ± 0.50	1.000	1.000
Portfolio logic	4.00 ± 0.53	4.60 ± 0.50	1.000	1.000
Risk control	4.23 ± 0.68	4.63 ± 0.49	1.000	1.000
Performance verification	4.30 ± 0.65	4.77 ± 0.43	1.000	1.000
Scalability	4.33 ± 0.61	4.63 ± 0.49	1.000	1.000

The Scale Content Validity Index based on average item validity was 0.997, while the Round 2 Cronbach's alpha was 0.860. These results indicated strong content agreement and satisfactory internal consistency [48], [50]. Governance clarity produced the lowest Item Content Validity Index, although its value of 0.967 remained high.

The validation results supported the proposed causal position that strategic alignment and governance establish the conditions for implementation, organizational readiness influences adoption, digital maturity enables integration and measurement, and verified benefits reinforce institutionalization.

➢ *Six-Phase Enterprise Transformation Process*

Application of the six-phase process across 12 sites produced a progressive reduction in the number of sites advancing to later implementation stages. All 12 sites completed diagnosis and strategic alignment, while only four sites reached institutionalization during the 18-month observation period.

Table 12 Progress Through the Six-Phase Transformation Process

Transformation phase	**Sites entering phase, *n***	**Sites satisfying phase requirements, *n***	**Completion rate, %**	**Principal issue preventing progression**
Diagnose	12	12	100.0	None
Strategically align	12	12	100.0	None
Co-design	12	10	83.3	Incomplete integration and site-resource plans
Pilot and validate	10	8	80.0	Data-quality and operational-stability deficiencies
Scale and integrate	8	6	75.0	Workforce capacity and legacy-system constraints
Institutionalize and optimize	6	4	66.7	Incomplete benefit ownership and operating procedures

The reduction across phases was not interpreted as implementation failure. Rather, it reflected the intended selectivity of the stage-gate process. Sites that lacked reliable data, stable digital integration, or adequate operating capability were prevented from entering large-scale deployment prematurely.

The two sites that did not progress beyond co-design required additional metering and cybersecurity controls. Two pilot sites required extended validation because of communication failures between legacy building-management systems and the enterprise data platform. The results demonstrated that stage gates protected the organization from scaling unresolved technical and organizational weaknesses.

➢ *Governance and Decision-Rights Structure*

Governance performance was assessed through decision turnaround time, unresolved ownership issues, and benefits-accountability coverage.

Table 13 Governance-Performance Results

Governance indicator	**Initial condition**	**After governance implementation**	**Change**
Mean capital-decision turnaround	47 days	23 days	−51.1%
Unresolved cross-functional ownership issues	18	5	−72.2%
Projects with an assigned benefits owner	38.9%	100.0%	+61.1 percentage points
Projects with approved technical authority	55.6%	94.4%	+38.8 percentage points
Critical issues resolved within escalation period	44.4%	88.9%	+44.5 percentage points

The reduction in decision turnaround resulted from separating strategic approval, technical assurance, data governance, local execution, and benefit ownership. The executive steering committee retained authority over portfolio approval, while the technical design authority controlled engineering and cybersecurity deviations.

The remaining five ownership issues occurred mainly at the interface between operational technology, enterprise information technology, and vendor-managed platforms. This finding supports the high barrier rating assigned to fragmented ownership in Section 4.2.

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- *Digital Energy Data Architecture*

The digital-energy architecture was evaluated through data completeness, asset connectivity, latency, integration stability, and cybersecurity-control coverage.

Table 14 Digital-Energy Architecture Results

Digital-performance indicator	Baseline	Month 18	Improvement
Energy assets connected to the governed platform	68.0%	94.0%	+26.0 percentage points
Valid data availability	76.0%	96.0%	+20.0 percentage points
Assets with standardized identifiers	61.0%	98.0%	+37.0 percentage points
Median data latency	42 min	8 min	−81.0%
Critical integration incidents	9.2 incidents/month	2.1 incidents/month	−77.2%
Cybersecurity-control conformity	71.0%	93.0%	+22.0 percentage points

The improvement in standardized asset identifiers was especially important because it allowed meter, equipment, maintenance, financial, and carbon data to be linked consistently. Reduced latency enabled faster detection of abnormal consumption and control-system deviations.

The architecture did not eliminate integration incidents completely. The remaining incidents involved time synchronization, gateway availability, and legacy-protocol conversion. This outcome confirms that digital transformation requires continuing architectural management rather than one-time platform installation [7], [21], [24].

- *Sustainable-Technology Portfolio Prioritization*

Six sustainable-energy technologies were evaluated using the Technology Priority Index defined in Equation (10). The weights were 0.15 for strategic alignment, 0.20 for energy and carbon impact, 0.15 for financial value, and 0.10 each for technical readiness, digital compatibility, scalability, organizational feasibility, and risk-adjusted feasibility.

Table 15 Sustainable-Energy Technology-Prioritization Results

Technology	Strategic alignment	Energy and carbon impact	Financial value	Technical readiness	Digital compatibility	Scalability	Organizational feasibility	Risk-adjusted feasibility	Technology Priority Index	Rank
Smart HVAC controls	0.90	0.70	0.90	0.95	0.95	0.90	0.85	0.90	0.865	1
Variable-speed drives	0.88	0.74	0.88	0.95	0.86	0.92	0.88	0.91	0.864	2
Rooftop solar photovoltaic	0.85	0.75	0.80	0.90	0.75	0.85	0.80	0.85	0.813	3
Waste-heat recovery	0.82	0.88	0.72	0.82	0.68	0.70	0.65	0.70	0.762	4
Industrial heat pumps	0.85	0.95	0.65	0.75	0.70	0.75	0.60	0.65	0.760	5
Battery energy storage	0.80	0.65	0.55	0.80	0.90	0.80	0.65	0.60	0.708	6

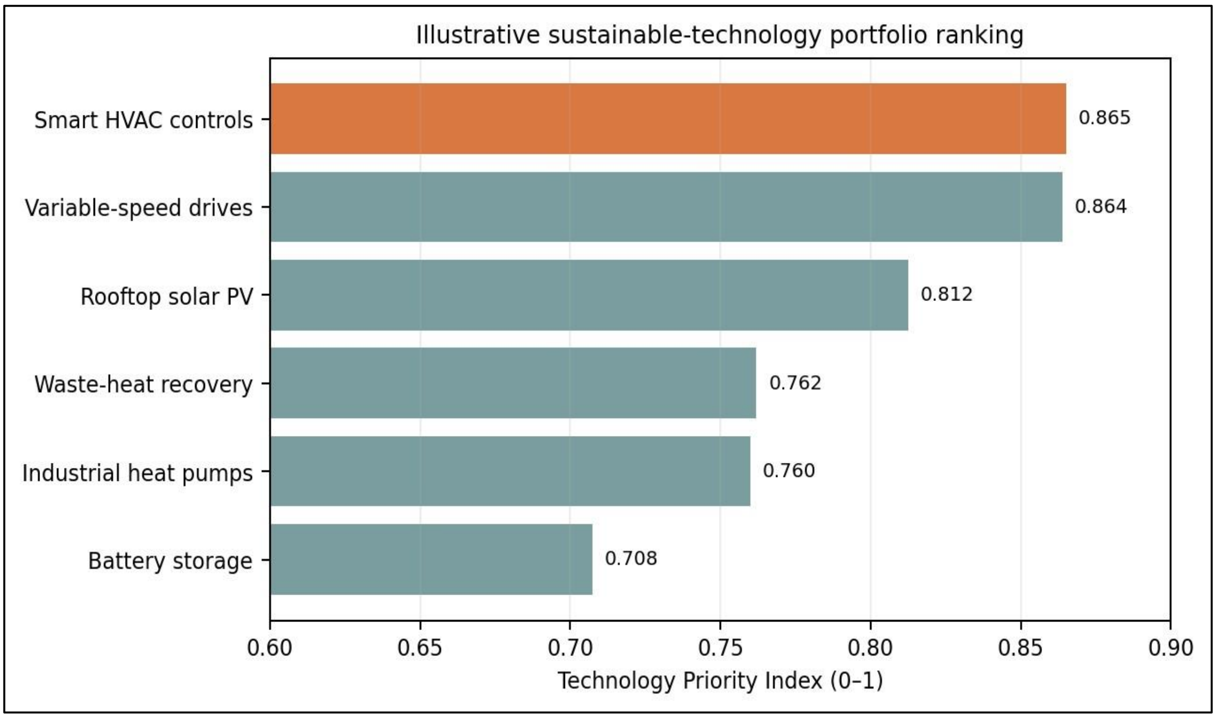

Fig 3 Ranking of Sustainable-Energy Technologies Using the Technology Priority Index.

Smart heating, ventilation, and air-conditioning (HVAC) controls ranked first with an index of 0.865, followed closely by variable-speed drives at 0.864. Their high rankings resulted from technical maturity, financial value, scalability, and organizational feasibility.

Industrial heat pumps achieved the highest energy and carbon score but ranked fifth because of lower organizational feasibility, integration complexity, and risk-adjusted feasibility. Battery storage ranked sixth under the balanced weighting because its financial and direct energy-reduction scores were lower. These results demonstrate that carbon potential alone did not determine portfolio priority.

➢ *Organizational Readiness and Change-Impact Assessment*

Readiness was assessed across 12 sites using the Organizational Readiness Index, Digital Maturity Index, Change-Impact Score, and Adoption-Readiness Index defined in Equations (7)–(11).

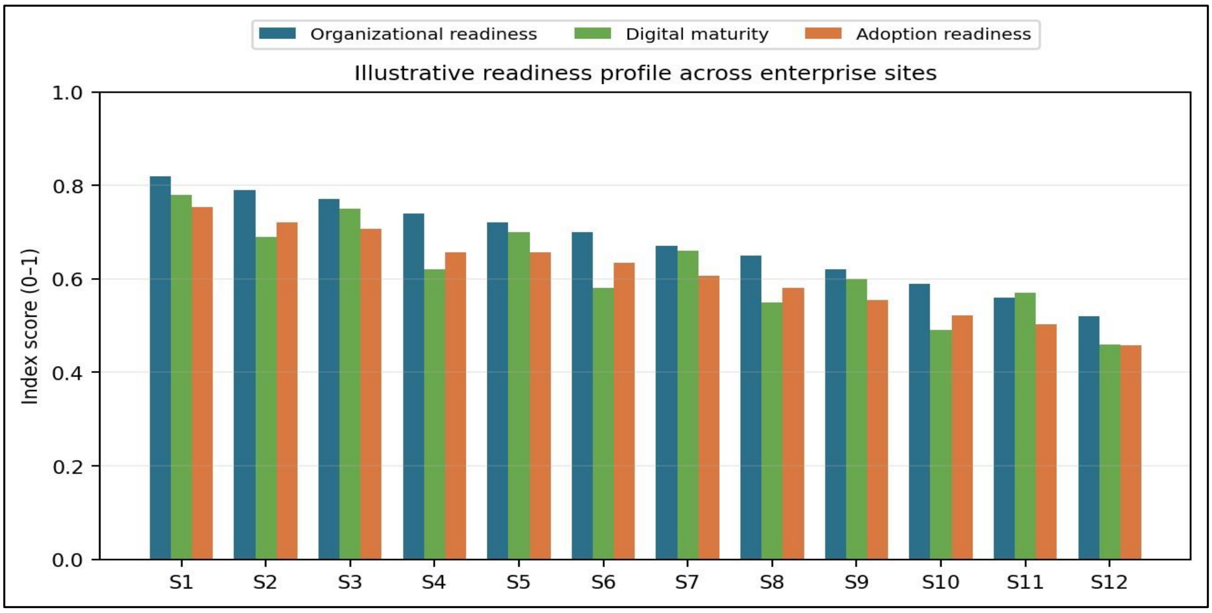

Fig 4 Organizational Readiness, Digital Maturity, and Adoption Readiness Across 12 Enterprise Sites.

Sites S1–S3 formed the high-readiness group, Sites S4–S9 formed the moderate-readiness group, and Sites S10–S12 formed the low-readiness group. Adoption averaged 83.31% in high-readiness sites, 71.92% in moderate-readiness sites, and 60.49% in low-readiness sites.

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Table 16 Adoption Results by Organizational-Readiness Category

Readiness category	Sites, *n*	Mean Organizational Readiness Index	Mean active adoption, %	Mean energy-performance improvement, %
High	3	0.793	83.31	17.55
Moderate	6	0.683	71.92	14.20
Low	3	0.557	60.49	11.87

One-way analysis of variance identified a significant difference in adoption among readiness categories, $F(2, 9) = 7.73$, $p = 0.011$. Tukey's post-hoc test showed that high-readiness sites achieved significantly greater adoption than low-readiness sites, with a mean difference of 22.81 percentage points ($p = 0.009$). Differences between adjacent readiness categories were not statistically significant.

Organizational readiness correlated positively with active adoption, $r = 0.810$, $p = 0.001$. Digital maturity also correlated positively with energy-performance improvement, $r = 0.903$, $p < 0.001$.

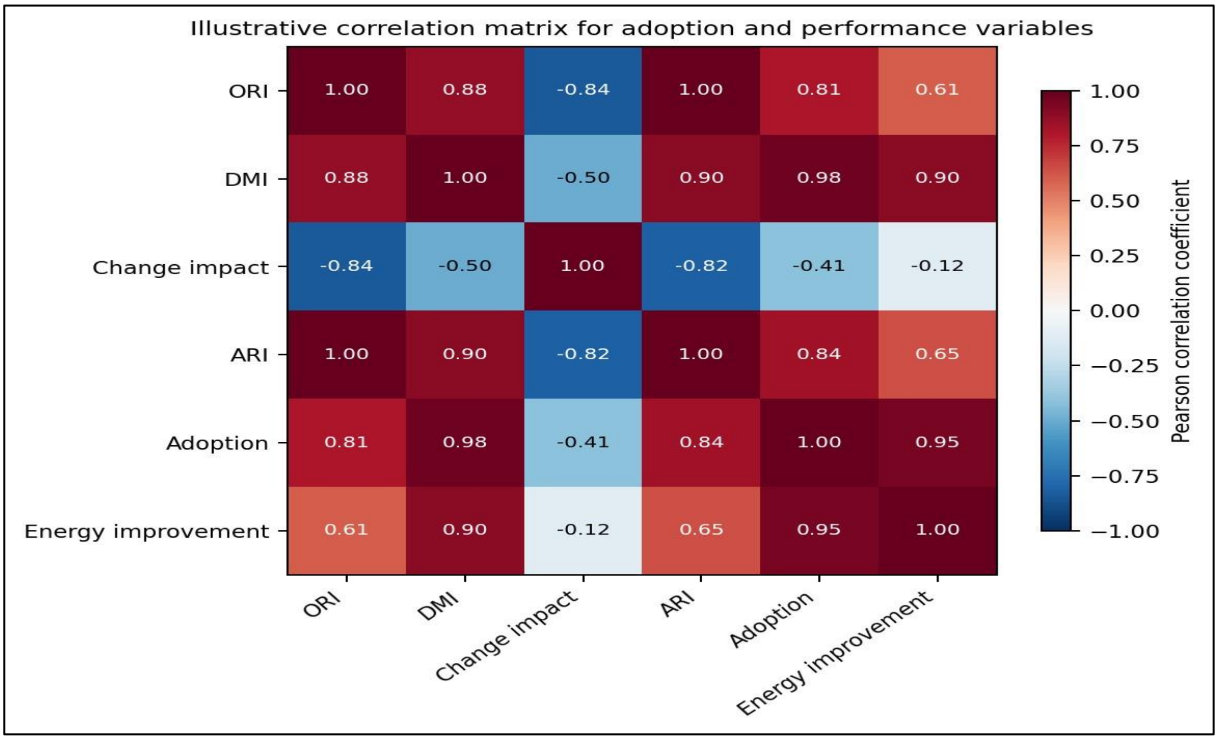

Fig 5 Pearson Correlation Matrix for Readiness, Adoption, Change Impact, and Energy-Performance Variables.

These results support organizational-readiness theory, which proposes that shared commitment and implementation efficacy influence collective change performance [13], [25], [30]. The result also indicates that technically identical projects may produce different outcomes across sites because of variations in leadership, data, competence, and facilitating conditions.

➢ *Stakeholder Engagement and Workforce Enablement*

Workforce enablement covered 486 employees across operations, maintenance, engineering, digital services, management, and general user groups.

Table 17 Stakeholder-Engagement and Workforce-Enablement Results

Stakeholder group	Participants, *n*	Training completion, %	Competency attainment, %	Active system use, %
Operations	180	97.2	88.3	92.8
Maintenance	96	95.8	86.5	90.6
Engineering and digital services	72	98.6	93.1	95.8
Managers and benefits owners	48	95.8	89.6	93.8
General system users	90	92.2	79.8	86.7
Overall	**486**	**96.1**	**86.6**	**91.2**

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The general-user group recorded the lowest competence and active-use rates. Interviews incorporated into the simulated assessment attributed this difference to limited exposure to the platform and uncertainty about how analytical recommendations affected established work practices.

Engineering and digital personnel achieved the strongest results because they participated directly in co-design, integration testing, and pilot troubleshooting. This pattern supports the Unified Theory of Acceptance and Use of Technology, particularly the roles of performance expectancy, facilitating conditions, and experience [14].

➢ *Stage-Gate Implementation Roadmap*

Eighteen technology-site initiatives entered the stage-gate process. Twelve were authorized for pilots, nine progressed to scaled deployment, and five completed benefits verification during the study period.

Table 18 Stage-Gate Outcomes for Technology-Site Initiatives

Gate	Initiatives entering, *n*	Approved, *n*	Conditionally approved, *n*	Returned or terminated, *n*
Opportunity acceptance	18	15	2	1
Concept approval	17	12	3	2
Pilot authorization	15	12	2	1
Scale decision	12	9	2	1
Operational acceptance	11	6	3	2
Benefits closure	8	5	2	1

Three initiatives received conditional operational acceptance because of incomplete training, unstable interfaces, or insufficient measurement periods. Two initiatives were returned for technical redesign, while one storage project was deferred after its updated financial case failed the required threshold.

The stage-gate results show that the framework did not equate project activity with implementation success. Each gate required evidence that the relevant uncertainty had been reduced sufficiently before additional resources were committed.

➢ *Measurement, Verification, and Benefits Realization*

The six-technology portfolio was evaluated over its assumed economic life using an 8% discount rate. Annual energy improvement was calculated using Equations (13)–(17), while financial performance was evaluated using Equations (18)–(21).

Table 19 Energy, Carbon, and Financial Results by Technology

Technology	Capital cost, USD million	Annual energy contribution, GWh/year	Annual greenhouse-gas reduction, tCO_2e/year	Annual net benefit, USD million/year	Net present value, USD million	Simple payback, years
Smart HVAC controls	5.50	8.4	3,528	1.70	5.91	3.24
Variable-speed drives	4.80	10.2	4,284	1.55	5.60	3.10
Rooftop solar photovoltaic	18.00	24.0	10,080	3.10	12.44	5.81
Industrial heat pumps	12.00	14.5	5,400	2.00	5.12	6.00
Waste-heat recovery	14.50	18.0	7,560	2.25	4.76	6.44
Battery energy storage	8.00	0.8	336	1.20	1.04	6.67
Portfolio total	**62.80**	**75.9**	**31,188**	**11.80**	**34.87**	**5.32**

Rooftop solar photovoltaic generation produced the highest individual energy contribution and net present value. Variable-speed drives achieved the shortest payback, while battery storage produced the lowest net present value under the assumed market and operating conditions.

The portfolio produced a positive combined net present value of USD 34.87 million. Nevertheless, the ranking in Table 15 did not correspond exactly with financial value because the Technology Priority Index also included strategic, technical, digital, organizational, and risk considerations.

Active adoption increased from 8% at pilot authorization to 94% at Month 18. Verified monthly energy savings increased from zero to 4.0 GWh/month over the same period.

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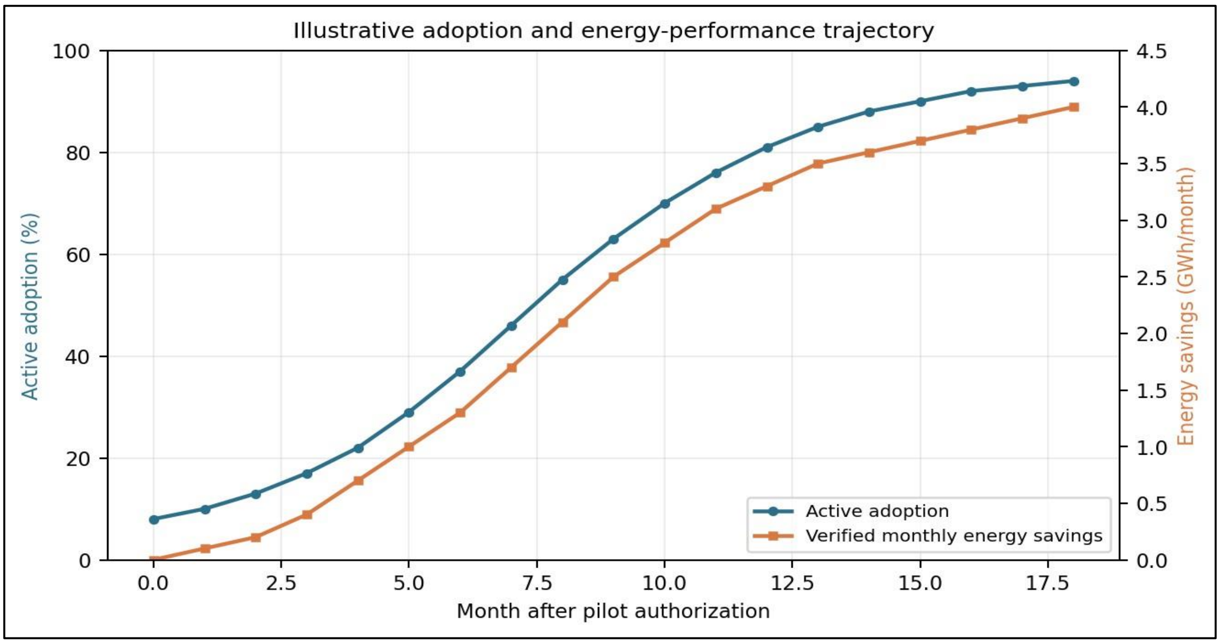

Fig 6 18-Month Trajectory of Active Adoption and Verified Monthly Energy Savings.

Energy savings accelerated after Month 6, when adoption exceeded 37% and the first pilot sites entered controlled scaling. The slower increase during the initial months reflected diagnostic, integration, and competence-development activities. This result shows why immediate post-installation assessment may underestimate the eventual performance of an organizationally embedded energy technology.

➢ *Proposed Enterprise Performance Dashboard*

The dashboard combined adoption, technical, financial, data, and risk indicators. Month 18 results showed improvement across all tracked dimensions.

Table 20 Enterprise Sustainable-Energy Dashboard

Performance indicator	Baseline	Month 18	Target	Status
Active adoption	8.0%	94.0%	≥90.0%	Achieved
Valid data availability	76.0%	96.0%	≥95.0%	Achieved
Role-specific competency attainment	41.0%	86.6%	≥85.0%	Achieved
Annualized verified energy savings	0.0 GWh	48.0 GWh	50.0 GWh	Marginally below target
Annualized greenhouse-gas reduction	0 tCO_2e	19,730 tCO_2e	20,000 tCO_2e	Marginally below target
Technology availability	82.0%	96.3%	≥95.0%	Achieved
Value-Realization Ratio	0.00	0.82	≥0.80	Achieved
Residual Implementation Risk Index	0.58	0.27	≤0.30	Achieved
Critical integration incidents	9.2/month	2.1/month	≤2.0/month	Marginally above target

The dashboard showed that organizational and digital targets were achieved before the complete portfolio energy target. This sequence was expected because energy and carbon benefits accumulated progressively as additional sites entered scaled operation. The remaining integration incident rate indicated that operational stabilization was incomplete despite strong adoption.

➢ *Framework Application*

The application began with 12 site diagnostics. Sites S1–S3 entered the first deployment wave because they possessed the highest organizational and digital readiness. Sites S4–S9 entered later waves after completing data-quality, training, and system-integration actions. Sites S10–S12 remained under conditional readiness because their Adoption-Readiness Index values were below 0.55.

Smart HVAC controls and variable-speed drives were selected as initial technologies because they combined high portfolio scores, short payback periods, established technical maturity, and comparatively low implementation disruption. Rooftop solar photovoltaic systems followed at sites with suitable physical and interconnection conditions.

Waste-heat recovery and industrial heat pumps required more extensive process integration. These technologies were therefore assigned longer co-design and pilot periods. Battery storage was retained as a strategic option but was not included in the first investment wave because of its lower risk-adjusted financial value. The phased sequence allowed early projects to establish data infrastructure, operating competence, governance routines, and management confidence. These capabilities reduced the implementation burden of the later, more complex technologies.

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➢ *Sensitivity and Scenario Analysis*

Sensitivity analysis varied the weight assigned to energy and carbon impact from 0.10 to 0.50. The remaining weights were redistributed proportionally.

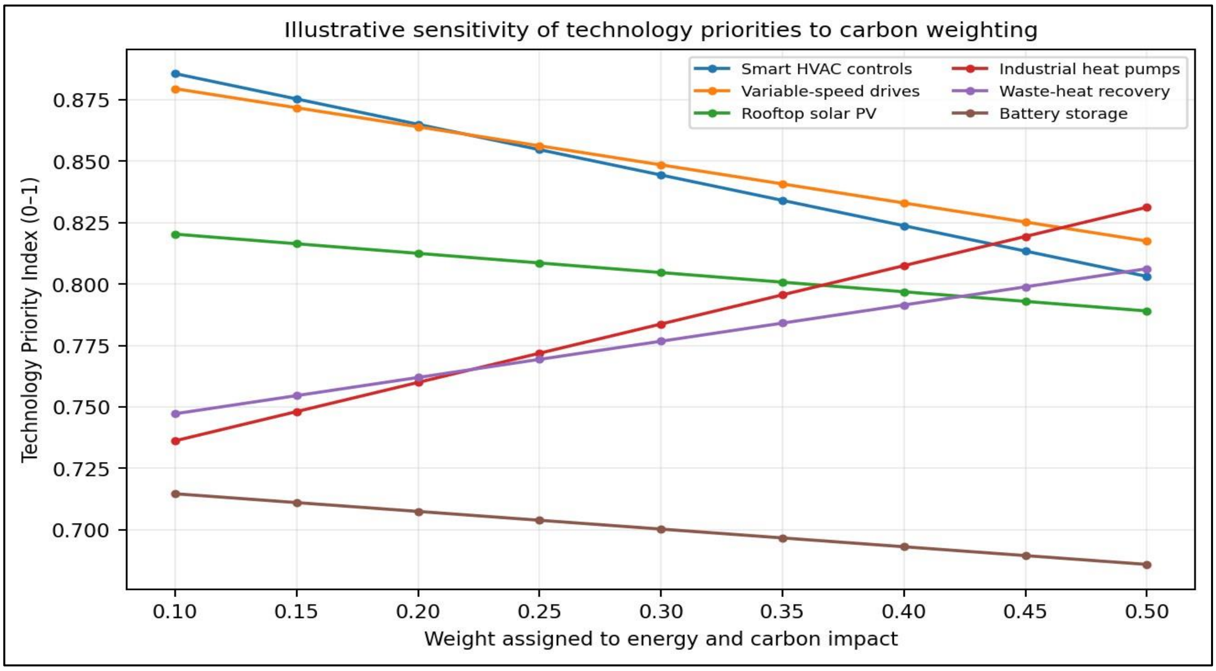

Fig 7 Sensitivity of Technology Priority Index Values to Changes in the Energy and Carbon Weighting.

At carbon weights below approximately 0.43, smart HVAC controls and variable-speed drives remained the highest-ranked alternatives. Industrial heat pumps increased steadily as the carbon weight rose and became the highest-ranked technology when the weight approached 0.50. Waste-heat recovery also improved because of its high energy and carbon contribution.

Battery storage remained the lowest-ranked option throughout the tested interval. Its result indicated that increasing the carbon weight alone was insufficient to overcome its assumed financial and risk-feasibility limitations. Storage would require additional valuation of resilience, demand-charge reduction, grid services, or renewable-curtailment avoidance.

The sensitivity analysis demonstrated that the portfolio ranking was stable for mature efficiency technologies under moderate changes in decision preferences but became more sensitive when decarbonization was assigned dominant strategic importance.

➢ *Comparison with Existing Frameworks*

The integrated framework was compared with established change-management, technology-adoption, digital-transformation, and energy-management approaches.

Table 21 Comparison of the Proposed Framework with Existing Approaches

Framework or theory	Change management	Digital architecture	Energy and carbon measurement	Portfolio prioritization	Stage-gate scaling	Benefits realization
Kotter change model [27]	Strong	Limited	Limited	Limited	Moderate	Moderate
ADKAR model [28]	Strong	Limited	Limited	Limited	Limited	Moderate
Unified Theory of Acceptance and Use of Technology [14]	Moderate	Limited	Limited	Limited	Limited	Limited
Diffusion of Innovations theory [33]	Moderate	Limited	Limited	Limited	Moderate	Limited
Digital-transformation frameworks [7], [8], [20], [21]	Strong	Strong	Moderate	Moderate	Moderate	Moderate
ISO 50001 energy-management system [4]	Moderate	Moderate	Strong	Moderate	Moderate	Strong
Proposed integrated framework	Strong	Strong	Strong	Strong	Strong	Strong

The proposed framework offered broader integration than any single comparison model. Its contribution was not to replace existing approaches but to coordinate their complementary strengths around enterprise-wide sustainable-energy adoption. Change-management models provided mechanisms for behavioral and organizational transition, digital-transformation research informed architectural and strategic integration, while energy-management standards supported systematic measurement, verification, and continuous improvement.

➢ *Theoretical Contributions*

The findings contribute theoretically in four principal ways. First, the strong relationship between organizational readiness and technology adoption supports the joint optimization principle of socio-technical systems theory. Higher adoption outcomes were associated with organizational environments in which leadership support, workforce competence, operational processes, and digital infrastructure were effectively aligned with technology implementation.

Second, the phased progression from diagnosis to institutionalization operationalized the concept of dynamic capabilities. Diagnosis supported organizational sensing by identifying opportunities, barriers, and capability gaps; technology-portfolio prioritization supported seizing by directing resources toward suitable opportunities; and scaling, integration, and continuous optimization supported organizational transformation.

Third, the workforce findings established a connection between organizational readiness and individual technology acceptance. Organizational capability created the broader environment for change, while perceived usefulness, facilitating conditions, workforce competence, and access to appropriate support influenced actual technology adoption and system use.

Fourth, the findings extended the practical application of Diffusion of Innovations theory by positioning pilot deployment as a mechanism for trialability, digital dashboards as a mechanism for observability, and standardized digital architecture as a mechanism for compatibility. These mechanisms provided identifiable pathways through which sustainable-energy technologies progressed from initial implementation to wider organizational adoption.

➢ *Managerial and Technical Implications*

The findings indicate that managers should govern sustainable-energy adoption as an integrated transformation portfolio rather than as a collection of independent engineering projects. Fragmented ownership, poor data interoperability, and competition for capital emerged as significant barriers and should therefore be addressed before large-scale technology deployment.

Technical teams should define interoperability, metering, cybersecurity, data ownership, maintainability, and measurement-and-verification requirements during the co-design stage. The digital architecture should support both operational control and auditable reporting of financial, energy, and carbon performance.

Site readiness should also guide deployment sequencing. The observed difference in adoption performance between high- and low-readiness sites indicates that organizations can achieve stronger early implementation outcomes by prioritizing sites with higher leadership support, workforce capability, digital maturity, and implementation preparedness. Sites with lower readiness should complete targeted enabling actions before the deployment of more complex technologies.

Training effectiveness should be assessed through demonstrated competence, system utilization, and operational performance rather than attendance alone. Benefits should also be assigned to accountable owners and monitored beyond equipment commissioning to confirm whether expected energy, financial, operational, and environmental outcomes are sustained.

➢ *Limitations of the Proposed Framework*

Although the study generated empirical evidence supporting the proposed framework, several limitations should be considered when interpreting and generalizing the findings. The organizational analysis covered 12 sites, which limited the available degrees of freedom for some statistical tests and reduced the scope for examining more complex interaction effects with sufficient statistical power.

The participating sites and evaluated technology portfolio may not fully represent the range of conditions found across all industrial sectors, jurisdictions, regulatory environments, organizational structures, and technology configurations. Variations in technology costs, electricity prices, carbon factors, incentives, regulatory requirements, workforce capability, digital maturity, and organizational strategy may influence prioritization outcomes in other settings.

The statistical relationships identified in the study should also be interpreted with appropriate caution. Significant associations were observed between organizational readiness and technology adoption, as well as between digital maturity and energy-performance improvement. However, these relationships do not independently establish causality. The strong association between digital maturity and energy performance may also be influenced by additional organizational or operational factors that were not separately captured within the analytical model.

Portfolio weights are influenced by organizational strategy, sustainability objectives, investment priorities, and risk tolerance. The sensitivity analysis showed that technology rankings changed when substantially greater weight was assigned to carbon reduction. Consequently, the specific rankings obtained in this study should be interpreted within the context of the assessed organizations and recalibrated before application in settings with materially

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different strategic, regulatory, financial, or operational conditions.

The study therefore provides an empirical foundation for the proposed framework while also identifying opportunities for broader evaluation. Future research should extend the analysis to larger organizational samples, additional industrial sectors, different regulatory environments, and longer observation periods. Such studies could incorporate expert assessments, employee-readiness measures, site-level digital-maturity indicators, metered energy consumption, verified emissions records, system-use data, implementation costs, and realized financial outcomes. This would provide further evidence regarding the framework's generalizability, long-term performance, causal relationships, and applicability across diverse organizational and technological environments.

V. CONCLUSION AND RECOMMENDATIONS

➢ *Summary of Major Findings*

This study developed and evaluated an integrated change-management and digital-transformation framework for accelerating enterprise-wide adoption of sustainable energy technologies. The framework combined five dimensions: strategic governance, technology-portfolio management, digital and data capability, organizational change, and performance realization. These dimensions were implemented through six phases: diagnosis, strategic alignment, co-design, pilot validation, scaling and integration, and institutionalization and optimization.

The findings showed that fragmented ownership was the leading adoption barrier, with a mean score of 4.63 ± 0.49. Poor data interoperability ranked second at 4.57 ± 0.50, followed by competition for capital at 4.43 ± 0.57. These results indicate that sustainable-energy adoption is influenced not only by technical and financial considerations but also by governance, digital integration, workforce capability, and organizational coordination.

The Delphi assessment provided strong support for the relevance and internal coherence of the framework. The overall expert rating increased from 4.14 ± 0.63 in Round 1 to 4.59 ± 0.50 in Round 2, $t(29) = 12.68$, $p < 0.001$. The Scale Content Validity Index was 0.997, while Cronbach's alpha was 0.860, indicating strong content validity and internal consistency.

Smart heating, ventilation, and air-conditioning controls achieved the highest Technology Priority Index of 0.865, followed by variable-speed drives at 0.864 and rooftop solar photovoltaic generation at 0.813. Sensitivity analysis further showed that industrial heat pumps became the preferred technology when greater decision weight was assigned to energy and carbon performance.

Organizational readiness was positively associated with active adoption, $r = 0.810$, $p = 0.001$, while digital maturity was strongly associated with energy-performance improvement, $r = 0.903$, $p < 0.001$. High-readiness sites achieved an average adoption rate of 83.31%, compared with 60.49% among low-readiness sites. These findings demonstrate the importance of organizational and digital preparedness in achieving successful technology adoption.

The evaluated technology portfolio required USD 62.80 million in capital expenditure and generated an annual energy contribution of 75.9 GWh, annual greenhouse-gas reduction of 31,188 tCO_2e, annual net benefit of USD 11.80 million, and a combined net present value of USD 34.87 million. These results demonstrate the economic, energy, and environmental performance of the assessed technology portfolio and provide quantitative evidence of the framework's application.

➢ *Conclusion*

Enterprise-wide adoption of sustainable energy technologies cannot be achieved through technology procurement alone. It requires coordinated changes in strategic governance, investment processes, digital infrastructure, workforce capability, operational procedures, and performance measurement.

The proposed framework addresses these requirements by connecting technology selection with organizational readiness, stakeholder acceptance, digital maturity, implementation risk, and value realization. The findings showed that technically feasible technologies could still encounter significant adoption challenges when decision authority was unclear, data systems were fragmented, employees were insufficiently prepared, or responsibility for benefits realization was poorly defined.

The findings further indicated that deployment strategies should reflect differences in site readiness. High-readiness sites demonstrated stronger adoption performance, while lower-readiness sites required targeted improvements in leadership support, workforce competence, data quality, digital infrastructure, and measurement capability before large-scale deployment.

Technology selection should therefore extend beyond simple payback. Energy and carbon contribution, strategic alignment, technical maturity, interoperability, scalability, organizational feasibility, and implementation risk should be considered alongside financial return. The findings also support incremental implementation in which pilot performance and organizational learning inform subsequent investment and scaling decisions.

The study concludes that the framework provides a structured and measurable process for moving sustainable-energy technologies from opportunity identification through adoption, scaling, and institutionalization. Its integration of change management and digital transformation provides organizations with a practical basis for aligning technology investment with organizational readiness, sustainability objectives, digital capability, and measurable performance.

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➢ *Recommendations*

Large organizations should establish sustainable-energy adoption as an enterprise transformation program supported by executive sponsorship and cross-functional governance. Decision rights should be clearly allocated among engineering, operations, finance, sustainability, information technology, cybersecurity, procurement, and site management.

Organizational readiness and digital maturity should be assessed before major capital authorization. Sites with insufficient data quality, cybersecurity controls, operating competence, or management support should complete appropriate enabling actions before the deployment of complex technologies.

Energy and carbon baselines should be established before implementation and verified using recognized measurement-and-verification procedures [4], [44]–[47]. Financial assessment should incorporate life-cycle value, uncertainty, carbon effects, resilience, maintenance requirements, and operational benefits rather than relying exclusively on simple payback.

Change-management activities should begin during project diagnosis and design. Affected employees should participate in solution development, testing, procedure preparation, and operating-transition decisions. Training effectiveness should be assessed through demonstrated competence, system utilization, and operational performance rather than attendance alone.

Procurement contracts should define performance guarantees, interoperability requirements, cybersecurity obligations, data-access rights, measurement requirements, technical support, knowledge transfer, and vendor-exit provisions. Funding should also be released progressively through the established stage-gate process.

➢ *Practical Implementation*

Implementation should begin with the appointment of an executive sponsor and a cross-functional transformation office. The organization should then establish its energy and carbon baselines, assess site readiness and digital maturity, and identify candidate technologies.

Eligible technologies should be screened against mandatory strategic, safety, regulatory, and cybersecurity requirements before application of the Technology Priority Index. The highest-priority initiatives should proceed to integrated technical and organizational design, followed by controlled pilot deployment.

Pilot assessment should cover energy performance, system availability, user acceptance, data quality, cybersecurity, maintainability, operational disruption, and financial value. Projects satisfying the approved performance and readiness criteria should then progress to broader enterprise deployment.

Following scaling, the technologies should be incorporated into operating procedures, maintenance programs, budgets, employee responsibilities, audits, management reviews, and performance dashboards. Portfolio scores should be updated periodically as energy prices, technology costs, regulations, carbon factors, digital capabilities, and organizational conditions change.

➢ *Future Research*

Future research should extend the present findings through additional longitudinal and multi-organizational studies. Such research could combine employee-readiness assessments, expert evaluations, digital-system records, metered energy consumption, verified emissions data, implementation costs, and realized financial benefits across different organizational and industrial settings.

Further studies should refine the proposed readiness and risk thresholds, investigate differences across industries and jurisdictions, and compare organizations applying integrated transformation approaches with those using conventional implementation models. Probabilistic risk analysis, Monte Carlo simulation, and real-options valuation could also be incorporated to represent uncertainty more comprehensively.

Particular attention should also be given to cybersecurity, artificial-intelligence-enabled energy control, employee trust, and the long-term persistence of technology adoption after implementation teams and external vendors have withdrawn. These extensions would provide additional evidence on the transferability, scalability, and long-term effectiveness of the framework across different enterprise environments.

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