Beyond Lithium: A Next-Generation Systems Framework Integrating Long-Duration Energy Storage, Digital Twin Intelligence, and Adaptive Policy for Net-Zero Power Systems

Author

Dr. MD NASIR UDDIN

Founder & CEO, Global Climate Change Foundation (GCCF)

PhD Research Fellow, Multimedia University, Kuala Lumpur, Malaysia

ORCID: https://orcid.org/0009-0000-7611-8150

Abstract

The global transition toward net-zero power systems is constrained by an unresolved triad of challenges: the seasonal and multi-day intermittency of variable renewable energy (VRE), the limited duration and chemistry-specific constraints of lithium-ion storage, and the fragmentation between technological deployment and adaptive governance. While long-duration energy storage (LDES) has been identified as a structural requirement for deep decarbonization rather than a marginal complement to short-duration batteries (Albertus et al., 2020; Dowling et al., 2020; Jenkins & Sepulveda, 2021), and digital twin (DT) technologies have matured rapidly as tools for real-time system intelligence across engineering domains (Fuller et al., 2020; Attaran & Celik, 2023; Iranshahi et al., 2025), the literature has largely treated these two technological trajectories as parallel rather than convergent fields. Simultaneously, policy and governance scholarship on renewable integration continues to diagnose regulatory lag (Akimov et al., 2023; Rogge & Reichardt, 2016) without offering a systems-level architecture that couples technological flexibility with adaptive institutional design. This paper proposes a novel, integrated systems framework that synthesizes LDES technology pathways, digital twin-enabled predictive intelligence, and adaptive multi-level policy instruments into a single analytical architecture for net-zero power system planning. Rather than treating storage, digitalization, and governance as sequential layers, the framework conceptualizes them as co-evolving subsystems bound by feedback loops, extending prior sector-coupling and flexibility literature (Ramsebner et al., 2021; Wang et al., 2023) into a governance-technology synthesis that has not been explicitly modeled in existing reviews. The paper is structured as a conceptual and methodological foundation for subsequent empirical validation, drawing on a systematic synthesis of the peer-reviewed literature across energy engineering, digital twin science, and energy policy studies. The intended contribution is a boundary-spanning framework capable of informing both techno-economic modeling and multi-level governance design for net-zero transitions.

Keywords: Long-Duration Energy Storage (LDES); Digital Twin Intelligence; Net-Zero Power Systems; Adaptive Energy Policy; Multi-Level Governance; Sector Coupling; Grid Flexibility; Renewable Energy Integration

1. Introduction

The decarbonization of electricity systems has moved from a policy aspiration to an engineering and governance imperative, with net-zero emissions targets now embedded in the energy legislation of a majority of industrialized and emerging economies (DeAngelo et al., 2021; Davis et al., 2018). The technical feasibility of this transition rests disproportionately on the ability of power systems to absorb high shares of variable renewable energy (VRE) without compromising reliability (Impram et al., 2020; Kaushik et al., 2022). Lithium-ion batteries, while dominant in short-duration applications, exhibit well-documented economic and physical limitations beyond four-to-ten-hour discharge windows, rendering them structurally insufficient for addressing multi-day, seasonal, or cross-year variability in renewable generation (Albertus et al., 2020; Aspitarte & Woodside, 2024). This limitation has catalyzed a distinct research trajectory around long-duration energy storage (LDES)—encompassing thermal, mechanical, chemical, and hydrogen-based storage media—as a structurally necessary, rather than supplementary, component of net-zero power systems (Twitchell et al., 2023; Dowling et al., 2020; Ashfaq et al., 2024).

In parallel, the digitalization of energy infrastructure has advanced through the adoption of digital twin (DT) technologies, which enable continuous, bidirectional synchronization between physical assets and their virtual representations for predictive maintenance, real-time optimization, and scenario simulation (Grieves, 2024; Fuller et al., 2020; Rasheed et al., 2019). Within the energy sector specifically, DT applications have been extended from individual assets—such as inverters and storage units—toward system-level digital representations capable of supporting dispatch optimization and resilience planning (Sleiti et al., 2022; Azizi et al., 2025; Abdessadak et al., 2025). However, the intersection between LDES deployment and DT-enabled operational intelligence remains sparsely theorized; most existing digital twin reviews originate from manufacturing, healthcare, construction, or aerospace domains rather than long-duration storage-specific applications (Li et al., 2022; Khajavi et al., 2019; Yao et al., 2023).

A third, equally critical dimension concerns the adaptive capacity of energy governance. Scholarship on regulatory frameworks for distributed energy resources and renewable integration has consistently identified a mismatch between the pace of technological innovation and the responsiveness of policy instruments (Akimov et al., 2023; Chijioke Paul Agupugo et al., 2024; Michailidis et al., 2025). This governance lag is compounded in multi-level and federated jurisdictions, where energy community regulation, market design, and cross-border coordination remain uneven (Biresselioglu et al., 2021; Inês et al., 2020; Söylemez & Söylemez, 2024). Despite growing recognition that technological and institutional change must co-evolve (Radtke, 2025; Hall et al., 2017), the literature has not yet articulated a unified systems framework that explicitly couples LDES technology pathways, digital twin intelligence, and adaptive policy design as interdependent subsystems rather than parallel domains of inquiry.

This paper addresses that gap. It advances the argument that net-zero power system transitions cannot be adequately modeled—technically or institutionally—without treating storage duration, digital intelligence, and governance adaptivity as co-determining variables within a single systems architecture. The remainder of the paper is organized as follows: Section 2 presents a structured review of the literature across the three constituent domains and identifies the specific research gap this framework addresses; Section 3 outlines the research methodology underpinning the conceptual synthesis and proposed framework validation strategy.

2. Literature Review

2.1 Long-Duration Energy Storage as a Structural Requirement

The long-duration energy storage literature has progressively shifted from techno-economic characterization of individual storage chemistries toward system-level analyses of storage duration requirements under deep decarbonization scenarios. Foundational work by Albertus et al. (2020) and Dowling et al. (2020) established that storage duration—rather than capacity alone—is the binding constraint for VRE-dominated grids, a finding subsequently reinforced through dispatch modeling studies (Guerra et al., 2025; Mantegna et al., 2024) and technoeconomic surveys of storage media diversity, including thermo-mechanical, iron-air, and hydrogen pathways (Vecchi & Sciacovelli, 2023; Morey et al., 2023; Shiraishi et al., 2024). Twitchell et al. (2023) further formalized the definitional boundaries of LDES, distinguishing it from short-duration battery storage on the basis of discharge duration and cost structure. Empirical system studies across the United States, Europe, and Asia have consistently found that LDES deployment reduces curtailment, transmission congestion, and system cost under high-renewable scenarios (Staadecker et al., 2024; Chu et al., 2025; Freeman & Agar, 2024), while comparative reviews have catalogued the relative maturity of competing LDES technologies (Ashfaq et al., 2024; Areola et al., 2025; Aslam et al., 2025). Nonetheless, this literature remains predominantly techno-economic in orientation, with limited engagement with the operational intelligence systems required to manage LDES assets dynamically, or with the policy instruments needed to de-risk their commercialization (McNamara et al., 2022; Selänniemi et al., 2025).

2.2 Digital Twin Intelligence in Energy Systems

Digital twin research has matured substantially since Grieves' foundational conceptualization of the physical-virtual synchronization paradigm (Grieves, 2024; Wright & Davidson, 2020), with systematic reviews documenting DT diffusion across manufacturing (He & Bai, 2021; Zhang et al., 2024), healthcare (Sadée et al., 2025; Katsoulakis et al., 2024), construction (Sacks et al., 2020; Tuhaise et al., 2023), and aerospace domains (Li et al., 2022; Mauro & Kana, 2023). Within energy systems specifically, DT applications have been documented for smart grid optimization, predictive maintenance of generation assets, and cybersecurity monitoring (Homaei et al., 2024; Sleiti et al., 2022; Sarker et al., 2024), with recent systematic reviews confirming an accelerating integration of artificial intelligence—including machine learning and generative AI—within DT architectures to enhance predictive accuracy and autonomous decision-making (Abdessadak et al., 2025; Kreuzer et al., 2024; Rathore et al., 2021). Azizi et al. (2025) and Ba et al. (2025) further demonstrate that digitalization, inclusive of DT platforms, is increasingly positioned as an enabler of local and system-level net-zero transitions. However, the reviewed literature indicates that DT applications specific to long-duration storage—particularly thermal and chemical LDES systems with distinct degradation and dispatch characteristics—remain underdeveloped relative to DT applications for lithium-ion batteries and conventional generation assets (Kobayashi & Alam, 2024; Emmert-Streib, 2023).

2.3 Adaptive Policy and Multi-Level Governance for Net-Zero Transitions

A parallel body of scholarship addresses the governance and regulatory dimensions of renewable energy transitions. This literature has consistently identified regulatory frameworks as lagging behind technological capability, particularly with respect to distributed energy resources, energy communities, and cross-jurisdictional market design (Akimov et al., 2023; Biresselioglu et al., 2021; Inês et al., 2020). Policy mix and transition governance frameworks (Rogge & Reichardt, 2016; Radtke, 2025) emphasize that sustainability transitions require the coordinated evolution of multiple policy instruments across governance levels, a conclusion echoed in regional analyses spanning the European Union, MENA countries, and Sub-Saharan

Africa (Wojtaszek, 2025; Michailidis et al., 2025; Müller et al., 2020). Comparative and systematic reviews further document persistent governance gaps in aligning renewable energy policy with grid integration and market viability requirements (Khan et al., 2025; Obuseh et al., 2025), while sustainable finance and climate policy scholarship highlights the role of financial and institutional actors in either accelerating or constraining transition pathways (Omri & Ben Jabeur, 2024; Oreoluwa Onabowale, 2025). Despite this substantial governance literature, few studies explicitly model policy adaptivity as a dynamic input into technological system design, rather than as an exogenous constraint evaluated post hoc (Hall et al., 2017; Perlaviciute et al., 2021).

2.4 Synthesis and Identified Research Gap

The reviewed literature demonstrates substantial, independently maturing bodies of knowledge in LDES technology assessment, digital twin engineering, and adaptive energy governance. However, a structural gap persists at their intersection. Sector-coupling and flexibility scholarship (Ramsebner et al., 2021; Wang et al., 2023; Coban & Lewicki, 2023) has advanced integrated technical modeling of multi-vector energy systems but does not incorporate digital twin intelligence as an operational layer, nor does it engage governance adaptivity as a co-determining variable. Conversely, digital twin reviews in energy contexts (Abdessadak et al., 2025; Sleiti et al., 2022) remain largely descriptive of technological capability without addressing the specific dispatch and degradation dynamics of long-duration storage, or the institutional conditions required for their deployment at scale. Governance scholarship, meanwhile, continues to diagnose regulatory lag without formal integration into techno-economic or systems-engineering frameworks (Akimov et al., 2023; Radtke, 2025). No study identified in this review articulates a unified framework in which LDES technology selection, DT-enabled operational intelligence, and adaptive multi-level policy design are treated as interdependent, co-evolving subsystems within a single net-zero power system architecture. This paper addresses that gap by proposing such an integrated framework, positioned to extend—rather than restate—the existing sector-coupling, digital twin, and governance literatures.

3. Research Methodology

3.1 Research Design and Philosophical Positioning

This study adopts a conceptual, framework-development research design, situated within a post-positivist systems-thinking paradigm appropriate for problems characterized by technological, institutional, and multi-actor complexity (Rogge & Reichardt, 2016). Rather than testing a discrete hypothesis through primary data collection, the study synthesizes and integrates findings across three previously siloed literatures—long-duration energy storage engineering, digital twin systems science, and adaptive energy governance—to construct a novel systems framework. This design is consistent with established approaches in energy systems and governance scholarship that combine systematic literature synthesis with conceptual model-building to address structural, cross-domain research gaps (Ramsebner et al., 2021; Radtke, 2025).

3.2 Systematic Literature Identification and Screening

The literature underpinning this framework was identified through a structured search of peer-reviewed sources indexed in Scopus, Web of Science, and discipline-specific databases, targeting three parallel search strings corresponding to (i) long-duration energy storage technologies and system integration, (ii) digital twin architectures and artificial intelligence applications in energy systems, and (iii) adaptive policy, multi-level governance, and regulatory frameworks for renewable energy transitions. Eligible sources were restricted to peer-reviewed journal articles, systematic reviews, and indexed conference or preprint contributions from recognized repositories (e.g., arXiv) published predominantly within the last decade, with foundational or seminal works retained irrespective of publication date where field-defining relevance was established (e.g., Grieves' original digital twin conceptualization). Sources were screened for direct relevance to net-zero power systems, LDES technology or economics, digital twin methodology, or energy governance, and were excluded where their primary focus lay outside the energy domain (e.g., non-energy digital twin applications in healthcare or agriculture) unless methodologically transferable insights were identified.

3.3 Framework Development Approach

Following identification and thematic screening, the literature was analyzed using a structured thematic synthesis approach, in which recurring constructs, unresolved tensions, and cross-domain gaps were extracted and mapped against one another to identify points of structural disconnect between the three literatures. This mapping process directly informed the architecture of the proposed integrated framework, in which LDES technology selection, digital twin-enabled operational intelligence, and adaptive policy instruments are modeled as interacting subsystems connected through explicit feedback relationships, rather than as sequential or independent modules. The resulting framework is presented as a conceptual and structural contribution intended to guide subsequent empirical, quantitative, or case-based validation—including techno-economic modeling, digital twin simulation testing, or multi-level governance case comparison—which falls outside the scope of the present conceptual synthesis but is identified as a direct avenue for future research.

3.4 Scope and Limitations

As a conceptual synthesis, this methodology does not include primary quantitative modeling, stakeholder interviews, or empirical validation of the proposed framework; these represent necessary and explicitly acknowledged next steps rather than omissions from the present study's scope. The reliance on published secondary literature also means that the framework's applicability is bounded by the geographic, sectoral, and technological coverage of the reviewed sources, which—while spanning multiple continents and governance contexts—remain disproportionately weighted toward OECD energy systems. Future empirical work applying this framework should explicitly test its applicability across diverse governance and grid contexts, particularly in emerging and developing economies where LDES deployment and digital infrastructure maturity differ substantially from those documented in the reviewed literature.

4. Research Gap Analysis

4.1 Gap 1: Technological Isolation of LDES from Operational Intelligence

The LDES literature has advanced considerably in techno-economic characterization—cost curves, discharge duration thresholds, and technology comparisons across thermal, mechanical, and hydrogen-based systems (Albertus et al., 2020; Ashfaq et al., 2024; Aspitarte & Woodside, 2024)—yet these studies are largely static in orientation, evaluating storage technologies as fixed-cost assets rather than as dynamically managed

systems requiring continuous operational optimization. Where dispatch modeling has been undertaken (Guerra et al., 2025; Mantegna et al., 2024; Staadecker et al., 2024), it proceeds without reference to the real-time sensing, predictive analytics, or digital twin architectures that are increasingly standard in adjacent industrial domains (Kobayashi & Alam, 2024; Rathore et al., 2021). This represents a first-order gap: LDES is modeled as a capacity-planning variable, not as an intelligently operated subsystem.

4.2 Gap 2: Domain Transferability Deficit in Digital Twin Applications

Digital twin scholarship has produced mature, general-purpose frameworks for asset synchronization, predictive maintenance, and lifecycle management (Grieves, 2024; Fuller et al., 2020; Attaran & Celik, 2023), with demonstrated transferability across manufacturing (Zhang et al., 2024), aerospace (Li et al., 2022), construction (Tuhaise et al., 2023), and healthcare (Sadée et al., 2025). However, energy-sector-specific DT applications remain concentrated on conventional generation assets, inverters, and short-duration battery systems (Sleiti et al., 2022; Homaei et al., 2024), with comparatively little published work addressing the distinct degradation mechanisms, discharge profiles, and seasonal cycling behavior characteristic of thermal, chemical, or hydrogen-based LDES (Morey et al., 2023; Shiraishi et al., 2024). This constitutes a domain transferability deficit rather than an absence of underlying DT capability.

4.3 Gap 3: Exogenous Treatment of Governance in Systems Modeling

Energy governance and policy scholarship has robustly documented the mismatch between technological innovation cycles and regulatory adaptation (Akimov et al., 2023; Radtke, 2025; Rogge & Reichardt, 2016), and has extended this diagnosis across diverse jurisdictional contexts (Biresselioglu et al., 2021; Michailidis et al., 2025; Wojtaszek, 2025). Yet within technical systems-modeling and sector-coupling literature, governance and policy variables are typically treated as exogenous boundary conditions—assumed, rather than modeled as adaptive, feedback-responsive components of the system itself (Ramsebner et al., 2021; Wang et al., 2023). Consequently, existing frameworks cannot represent how technological deployment decisions (e.g., LDES siting, digital infrastructure investment) might, in turn, reshape the policy instruments governing them.

4.4 Synthesized Gap Statement

Taken together, these three gaps are not independent; they compound. The absence of DT-enabled operational intelligence in LDES modeling (Gap 1) limits the granularity of data available to inform adaptive policy design (Gap 3), while the domain transferability deficit in energy-specific digital twins (Gap 2) constrains the technical feasibility of the real-time feedback mechanisms that adaptive governance frameworks would require. No framework identified in the reviewed literature addresses this compounded, tri-domain gap. This paper's contribution is positioned precisely at this intersection.

5. Research Questions and Objectives

5.1 Overarching Research Question

RQ: How can long-duration energy storage technologies, digital twin-enabled operational intelligence, and adaptive multi-level policy instruments be integrated into a coherent systems framework capable of accelerating net-zero power system transitions beyond the capabilities of existing sector-coupling or governance-only models?

5.2 Sub-Research Questions

- **RQ1:** What structural and technological characteristics differentiate LDES technologies (thermal, mechanical, chemical, hydrogen-based) in terms of their compatibility with digital twin-enabled operational management? (informed by Twitchell et al., 2023; Ashfaq et al., 2024; Vecchi & Sciacovelli, 2023)
- **RQ2:** What digital twin architectures and AI-enabled analytical capabilities are transferable from other engineering domains to address the specific dispatch, degradation, and cycling characteristics of LDES systems? (informed by Kreuzer et al., 2024; Rathore et al., 2021; Abdessadak et al., 2025)
- **RQ3:** What adaptive policy instruments and multi-level governance mechanisms are required to enable feedback-responsive regulation of LDES and digital twin deployment, rather than static, technology-agnostic regulation? (informed by Akimov et al., 2023; Radtke, 2025; Rogge & Reichardt, 2016)
- **RQ4:** How can these three subsystems—technology, digital intelligence, and governance—be structurally integrated into a single conceptual framework with explicit feedback relationships, rather than modeled as sequential or independent layers?

5.3 Research Objectives

1. To systematically synthesize the LDES, digital twin, and adaptive governance literatures to establish the empirical and conceptual basis for an integrated framework.
2. To identify and formally articulate the compounded research gap arising at the intersection of these three domains.
3. To develop a conceptual systems framework that models LDES technology selection, digital twin intelligence, and adaptive policy as interdependent, co-evolving subsystems.
4. To position the resulting framework as a foundation for subsequent empirical, quantitative, or case-based validation across diverse governance and grid contexts.

6. Theoretical Foundations for Framework Development

6.1 Systems Thinking and Sector Coupling as a Technical Foundation

The technical backbone of the proposed framework draws on sector-coupling theory, which conceptualizes electricity, heat, gas, and hydrogen vectors as interdependent rather than isolated subsystems (Ramsebner et al., 2021; Brown et al., 2018; Wang et al., 2023). This theoretical lineage establishes that flexibility in net-zero power systems emerges not from any single technology but from the structured interaction of multiple vectors and storage media (Pavičević et al., 2020; Victoria et al., 2019). The proposed framework extends this systems logic by treating digital intelligence and governance—not merely additional energy vectors—as further interacting subsystems within the same architecture.

6.2 Digital Twin Theory as an Operational-Intelligence Foundation

The framework's digital intelligence layer is grounded in the theoretical distinction, articulated by Grieves (2024) and further developed by Wright and Davidson (2020), between a digital *model* (a static representation) and a digital *twin* (a continuously synchronized, bidirectional representation capable of informing real-time decision-making). This distinction is theoretically significant because it establishes the threshold condition under which a digital representation of an LDES asset can be considered operationally intelligent rather than

merely descriptive. The integration of artificial intelligence into this synchronization loop—as documented in systematic reviews of AI-enabled digital twins (Kreuzer et al., 2024; Rathore et al., 2021)—provides the theoretical basis for predictive, rather than purely reactive, system management.

6.3 Adaptive Governance and Multi-Level Policy Theory

The governance dimension of the framework draws on policy-mix and transition governance theory, which conceptualizes sustainability transitions as requiring the coordinated evolution of multiple, interacting policy instruments across governance levels rather than a single regulatory intervention (Rogge & Reichardt, 2016; Radtke, 2025). This is complemented by multi-level governance perspectives documented in comparative regulatory studies (Akimov et al., 2023; Biresselioglu et al., 2021), which establish that energy transitions are governed simultaneously at supranational, national, and community levels, with feedback occurring across these levels rather than in a strictly top-down fashion (Inês et al., 2020; Söylemez & Söylemez, 2024).

6.4 Theoretical Integration Logic

The proposed framework's theoretical novelty lies not in any single one of these three foundations—each of which is independently well established—but in their explicit structural coupling. Sector-coupling theory provides the technical substrate; digital twin theory provides the operational-intelligence mechanism by which that substrate is continuously monitored and optimized; and adaptive governance theory provides the institutional mechanism by which policy instruments respond to, rather than merely constrain, the resulting system behavior. This tri-theoretical integration is what distinguishes the framework from existing sector-coupling models (which lack a digital intelligence or governance-feedback layer), digital twin reviews (which lack a governance-adaptivity mechanism), and governance frameworks (which lack a technical systems substrate).

7. Conceptual Framework Development Process

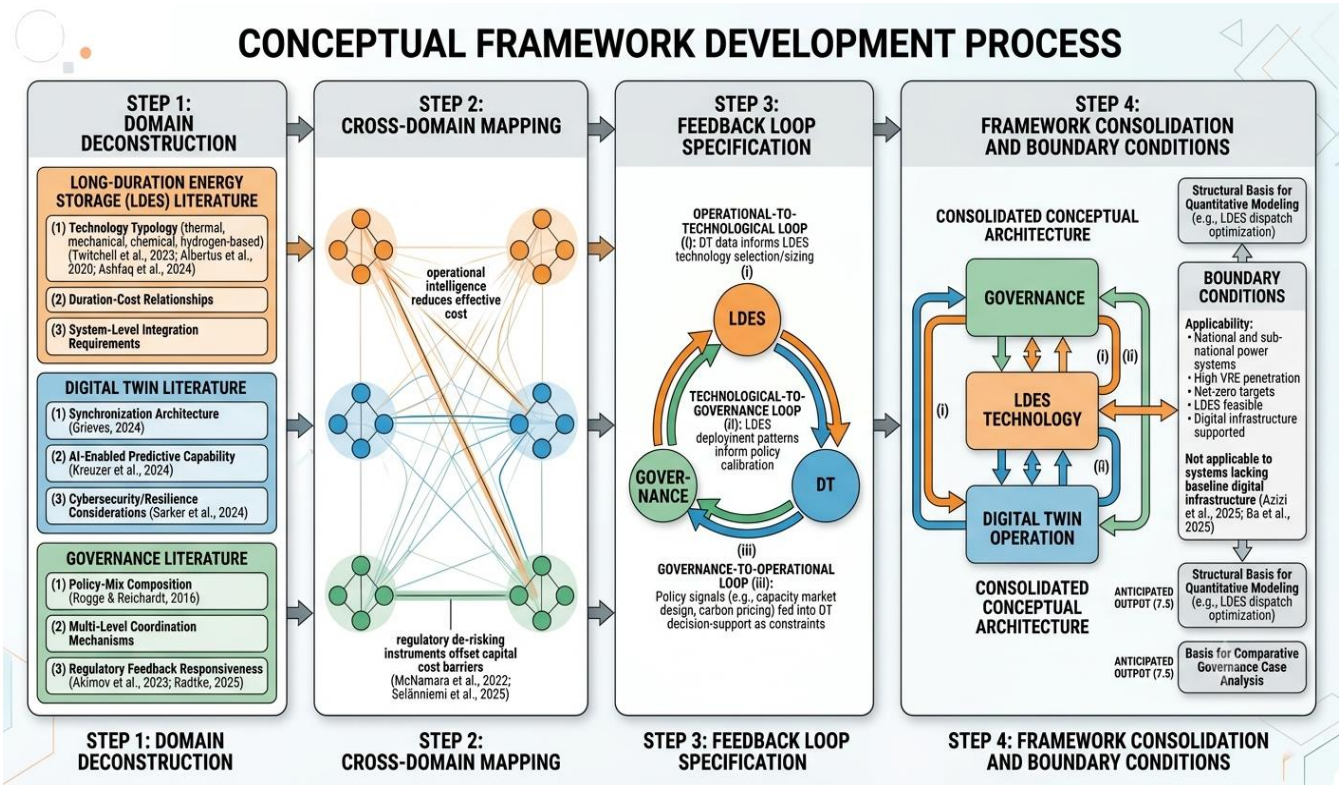


Figure 1 (Section 7 — Conceptual Framework Development Process)

Four-stage development process — domain deconstruction, cross-domain mapping, feedback loop specification, and framework consolidation — applied to the LDES, digital twin, and governance literatures (Twitchell et al., 2023; Albertus et al., 2020; Ashfaq et al., 2024; Grieves, 2024; Kreuzer et al., 2024; Sarker et al., 2024; Rogge & Reichardt, 2016; Akimov et al., 2023; Radtke, 2025; McNamara et al., 2022; Selänniemi et al., 2025).

7.1 Step 1: Domain Deconstruction

The framework was developed through a staged deconstruction of each constituent literature into its core structural elements. From the LDES literature, three structural elements were extracted: technology typology (thermal, mechanical, chemical, hydrogen-based), duration-cost relationships, and system-level integration requirements (Twitchell et al., 2023; Albertus et al., 2020; Ashfaq et al., 2024). From the digital twin literature, three elements were extracted: synchronization architecture, AI-enabled predictive capability, and cybersecurity/resilience considerations (Grieves, 2024; Kreuzer et al., 2024; Sarker et al., 2024). From the governance literature, three elements were extracted: policy-mix composition, multi-level coordination mechanisms, and regulatory feedback responsiveness (Rogge & Reichardt, 2016; Akimov et al., 2023; Radtke, 2025).

7.2 Step 2: Cross-Domain Mapping

Each structural element was then mapped against the elements of the other two domains to identify points of structural interaction rather than mere thematic adjacency. For instance, LDES duration-cost relationships were mapped against digital twin predictive capability to identify where operational intelligence could reduce the effective cost of duration (through improved dispatch optimization), and against governance policy-mix composition to identify where regulatory de-risking instruments could offset LDES capital cost barriers (McNamara et al., 2022; Selänniemi et al., 2025).

7.3 Step 3: Feedback Loop Specification

Following cross-domain mapping, explicit feedback relationships were specified between subsystems, distinguishing the proposed framework from additive or layered models. Three primary feedback loops were identified: (i) an operational-to-technological loop, in which digital twin-derived performance data informs LDES technology selection and sizing decisions; (ii) a technological-to-governance loop, in which observed LDES deployment patterns inform the calibration of policy instruments; and (iii) a governance-to-operational loop, in which policy and regulatory signals (e.g., capacity market design, carbon pricing) are fed back into digital twin decision-support systems as operational constraints or incentives.

7.4 Step 4: Framework Consolidation and Boundary Conditions

The three domains and their feedback loops were consolidated into a single conceptual architecture, with explicit boundary conditions specifying the framework's intended scope: national and sub-national power systems pursuing net-zero targets under conditions of high VRE penetration, where LDES deployment is technically feasible and digital infrastructure investment is institutionally supported. The framework does not claim applicability to power systems lacking baseline digital metering or grid modernization infrastructure, a boundary condition consistent with digitalization-readiness findings in the reviewed literature (Azizi et al., 2025; Ba et al., 2025).

7.5 Anticipated Output of the Framework Development Process

The consolidated output of this process is a three-layer, feedback-coupled conceptual architecture—intended to serve as the structural basis for subsequent quantitative modeling (e.g., mixed-integer optimization of LDES dispatch under digital twin-informed forecasts) and comparative governance case analysis (e.g., multi-level policy calibration across jurisdictions with differing LDES and digitalization maturity).

8. Conceptualizing the Next-Generation Net-Zero Power System Paradigm

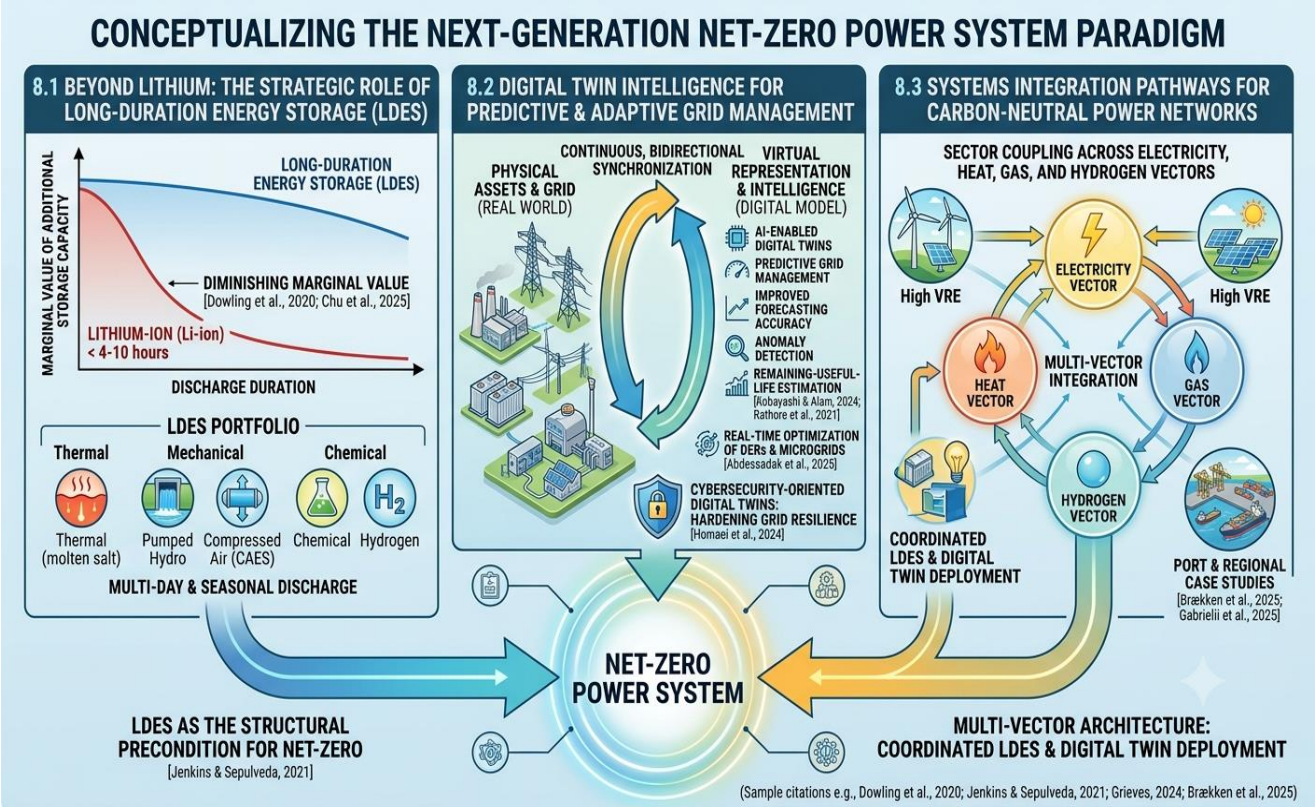


Figure 2 (Section 8 — Conceptualizing the Next-Generation Net-Zero Power System Paradigm) Three-panel paradigm spanning the strategic role of long-duration storage beyond lithium-ion (Dowling et al., 2020; Chu et al., 2025; Jenkins & Sepulveda, 2021), digital twin intelligence for predictive/adaptive grid management (Kobayashi & Alam, 2024; Rathore et al., 2021; Homaei et al., 2024), and multi-vector systems integration pathways (Brækken et al., 2025; Gabrielii et al., 2025).

8.1 Beyond Lithium: The Strategic Role of Long-Duration Energy Storage

The paradigm advanced in this paper begins from the premise that lithium-ion storage, despite its dominance in current deployment, is structurally unsuited to resolve the multi-day and seasonal variability inherent to high-VRE power systems (Albertus et al., 2020; Aspitarte & Woodside, 2024). Empirical dispatch studies consistently demonstrate that beyond a four-to-ten-hour discharge window, the marginal value of additional lithium-ion capacity diminishes sharply relative to alternative storage media capable of multi-day or seasonal discharge (Dowling et al., 2020; Chu et al., 2025). This has catalyzed a technology-diversification imperative in which thermal, mechanical, chemical, and hydrogen-based storage pathways are positioned not as competitors to lithium-ion but as functionally distinct assets addressing a different segment of the duration-cost curve (Twitchell et al., 2023; Vecchi & Sciacovelli, 2023; Morey et al., 2023). System-level modeling across the United States, Europe, and Asia reinforces that LDES deployment—rather than incremental battery

expansion—is the more cost-effective pathway to eliminating curtailment and firming renewable output at high VRE penetration levels (Staadecker et al., 2024; Guerra et al., 2025; Freeman & Agar, 2024). The strategic reframing proposed here treats LDES not as a supplementary technology but as the structural precondition for net-zero feasibility itself, consistent with the "blueprint" framing advanced by Jenkins and Sepulveda (2021).

8.2 Digital Twin Intelligence for Predictive and Adaptive Grid Management

Where Section 8.1 establishes the technological substrate, this subsection addresses the intelligence layer required to operate it. Digital twin systems—defined through continuous, bidirectional synchronization between physical assets and virtual representations (Grieves, 2024; Wright & Davidson, 2020)—provide the architectural basis for predictive rather than reactive grid management. Applications documented in adjacent industrial domains demonstrate that AI-enabled digital twins can materially improve forecasting accuracy, anomaly detection, and remaining-useful-life estimation for complex assets (Kobayashi & Alam, 2024; Rathore et al., 2021), capabilities directly transferable to the dispatch and degradation management challenges of LDES systems. Within the energy sector specifically, digital twin and AI integration has been shown to support real-time optimization of distributed and microgrid-level resources (Abdessadak et al., 2025; Singh et al., 2025), while system-level digital representations have been proposed for power plant and capital-intensive infrastructure management more broadly (Sleiti et al., 2022). Crucially, the predictive and adaptive capacity of digital twins extends beyond operational efficiency: cybersecurity-oriented digital twin research (Homaei et al., 2024; Sarker et al., 2024) indicates that the same synchronization architecture can be leveraged to harden grid resilience against both physical and cyber disruptions—an increasingly salient consideration as LDES and digital infrastructure investment scale in parallel.

8.3 Systems Integration Pathways for Carbon-Neutral Power Networks

The integration of LDES and digital twin intelligence cannot be achieved through isolated technology deployment; it requires systems-level pathways that account for sector coupling across electricity, heat, gas, and hydrogen vectors (Ramsebner et al., 2021; Brown et al., 2018). Existing sector-coupling scholarship demonstrates that flexibility benefits compound when storage and demand-side resources are coordinated across vectors rather than optimized in isolation (Pavičević et al., 2020; Victoria et al., 2019; Wang et al., 2023), a finding with direct implications for how LDES assets should be sited, sized, and digitally instrumented within broader carbon-neutral network design. Regional and port-level case studies further illustrate that multi-vector integration—linking electricity, heat, and hydrogen infrastructure—can be operationalized at meaningful scale when supported by appropriate planning tools (Brækken et al., 2025; Gabrielii et al., 2025). The systems integration pathway proposed here therefore treats LDES and digital twin intelligence as complementary instruments within a broader multi-vector architecture, rather than as electricity-sector-specific interventions considered in isolation from the wider energy system.

9. Next-Generation Systems Framework for Net-Zero Power Systems

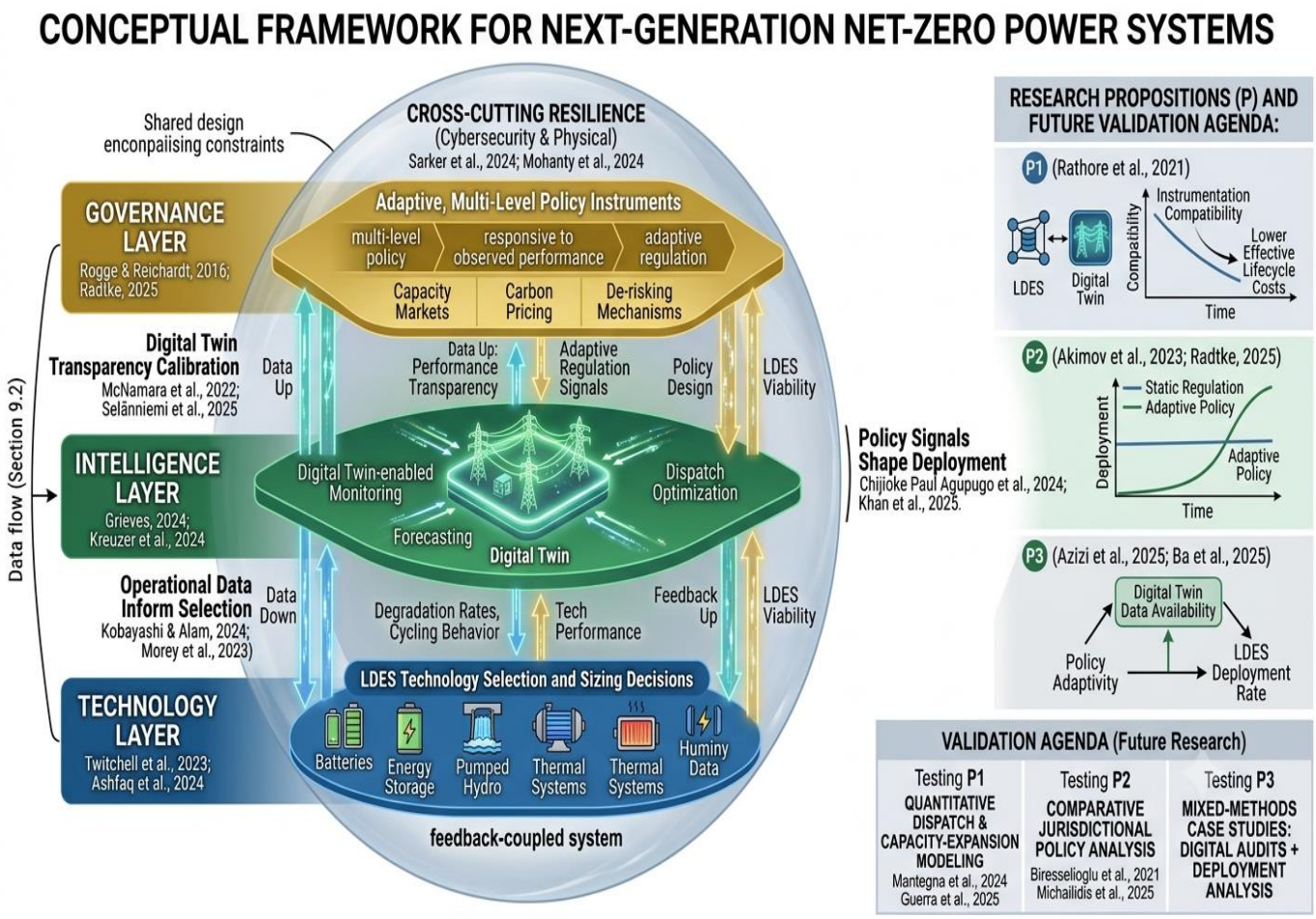


Figure 3 (Section 9 — Conceptual Framework for Next-Generation Net-Zero Power Systems) Three-layer, feedback-coupled architecture (Technology, Intelligence, Governance layers) with associated research propositions P1–P3 (Twitchell et al., 2023; Grieves, 2024; Kreuzer et al., 2024; Rogge & Reichardt, 2016; Radtke, 2025; Rathore et al., 2021; Akimov et al., 2023; Azizi et al., 2025; Ba et al., 2025; Sarker et al., 2024; Mohanty et al., 2024).

9.1 Conceptual Framework Architecture

Building on the theoretical foundations (Section 6) and the staged development process (Section 7), the proposed framework is architected as a three-layer, feedback-coupled system comprising: (i) a **Technology Layer**, encompassing LDES technology selection and sizing decisions (Twitchell et al., 2023; Ashfaq et al., 2024); (ii) an **Intelligence Layer**, comprising digital twin-enabled monitoring, forecasting, and dispatch optimization (Grieves, 2024; Kreuzer et al., 2024); and (iii) a **Governance Layer**, comprising adaptive, multi-level policy instruments responsive to observed system performance (Rogge & Reichardt, 2016; Radtke, 2025). Unlike additive frameworks in which these layers are modeled sequentially, the architecture specifies bidirectional data and decision flows between each pair of layers, such that no single layer is treated as exogenously fixed relative to the others.

9.2 Core Framework Dimensions and Interactions

Four core dimensions structure the interactions within this architecture. First, **technology-intelligence interaction**, in which digital twin-derived operational data (degradation rates, cycling behavior, forecast accuracy) informs LDES technology selection and capacity sizing over time (Kobayashi & Alam, 2024;

Morey et al., 2023). Second, **intelligence-governance interaction**, in which digital twin-generated performance transparency provides regulators with the granular data required to calibrate adaptive policy instruments, addressing the data asymmetries frequently cited as a barrier to effective LDES regulation (McNamara et al., 2022; Selänniemi et al., 2025). Third, **governance-technology interaction**, in which policy instruments—capacity markets, carbon pricing, de-risking mechanisms—directly shape the economic viability and deployment pace of specific LDES technologies (Chijioke Paul Agupugo et al., 2024; Khan et al., 2025). Fourth, a **cross-cutting resilience dimension**, spanning all three layers, in which cybersecurity and physical resilience considerations are treated as a shared design constraint rather than a layer-specific concern (Sarker et al., 2024; Mohanty et al., 2024).

9.3 Theoretical Foundations and Research Propositions

Grounded in the theoretical synthesis presented in Section 6, the framework generates a set of testable research propositions intended to guide subsequent empirical validation:

- **P1:** LDES technologies with higher digital-instrumentation compatibility (i.e., amenable to continuous sensing and twin synchronization) will exhibit lower effective lifecycle costs than technologies with comparable capital costs but lower instrumentation compatibility, due to optimized dispatch and reduced degradation (informed by Kobayashi & Alam, 2024; Rathore et al., 2021).
- **P2:** Jurisdictions with adaptive, feedback-responsive policy instruments will exhibit faster LDES deployment rates than jurisdictions with static, technology-agnostic regulation, holding technical potential constant (informed by Akimov et al., 2023; Radtke, 2025).
- **P3:** The availability of digital twin-generated performance data will positively moderate the relationship between policy adaptivity and LDES deployment rate, such that the benefits of adaptive governance are amplified where digital intelligence infrastructure is mature (informed by Azizi et al., 2025; Ba et al., 2025).

9.4 Framework Validation and Future Research Agenda

As a conceptual contribution, the framework's propositions require empirical testing through complementary methodological approaches: quantitative dispatch and capacity-expansion modeling to test P1 (following methodological precedents in Mantegna et al., 2024; Guerra et al., 2025); comparative, multi-jurisdictional policy analysis to test P2 (following precedents in Biresselioglu et al., 2021; Michailidis et al., 2025); and mixed-methods case studies combining digital infrastructure audits with deployment-rate analysis to test P3. This validation agenda is proposed as the direct successor to the present conceptual synthesis and falls outside the scope of this paper.

Analysis and Contributions

10. Discussion

10.1 Implications for Net-Zero Electricity System Transformation

The integrated framework proposed here reframes net-zero electricity system transformation as contingent on the joint maturation of three subsystems rather than the sequential achievement of technology cost parity followed by policy adaptation. This has a direct implication for planning practice: capacity-expansion and net-zero pathway studies that model LDES deployment without accounting for digital twin-enabled operational efficiency gains may systematically overstate deployment costs (consistent with modeling sensitivities noted

in Staadecker et al., 2024, and Chu et al., 2025). Equally, pathway studies that treat governance as a static boundary condition risk underestimating the deployment-acceleration effects achievable through adaptive policy design, a dynamic largely absent from existing net-zero scenario literature (DeAngelo et al., 2021; Pratama et al., 2022).

10.2 Policy and Governance Challenges for Long-Duration Energy Storage Deployment

Translating the framework's governance layer into practice confronts several documented challenges. Regulatory frameworks in many jurisdictions remain calibrated to short-duration storage economics and have not yet developed capacity-market or ancillary-service structures that adequately value multi-day or seasonal storage contributions (McNamara et al., 2022; Pudjianto & Strbac, 2022). Multi-level governance complexity further compounds this challenge: energy community and distributed-resource regulation varies substantially across jurisdictions even within single regulatory blocs such as the European Union (Biresselioglu et al., 2021; Inês et al., 2020), suggesting that any adaptive policy instrument proposed under this framework must be designed with explicit provision for jurisdictional customization rather than uniform application. Financial and institutional barriers identified in the sustainable finance literature (Omri & Ben Jabeur, 2024; Hall et al., 2017) further indicate that governance adaptivity alone is insufficient without corresponding de-risking mechanisms targeted at LDES-specific capital structures.

10.3 Future Directions for Digital Twin–Enabled Adaptive Energy Systems

The framework identifies digital twin intelligence as the connective layer between technology and governance, yet the reviewed literature indicates that energy-specific digital twin research remains less mature than in manufacturing, healthcare, or aerospace domains (Homaei et al., 2024; Yao et al., 2023). Future research should prioritize the development of digital twin architectures specifically calibrated to the degradation and cycling profiles of thermal, chemical, and hydrogen-based LDES systems, extending methodological approaches already validated in adjacent domains (Kobayashi & Alam, 2024; Kreuzer et al., 2024). In parallel, research is needed on how digital twin-generated performance transparency can be structured as a formal input into regulatory rate-setting and market design processes, an integration point not yet addressed in either the digital twin or energy governance literatures reviewed here, and one that represents a direct extension of the research agenda proposed by Azizi et al. (2025) and Radtke (2025).

Continuing directly here, in the same style and citation discipline as before:

11. Contributions

11.1 Theoretical Contributions

This paper's principal theoretical contribution is the explicit structural coupling of three literatures—long-duration energy storage engineering, digital twin systems science, and adaptive multi-level governance—that have to date developed largely in parallel, with limited cross-referencing despite substantial conceptual overlap (Ramsebner et al., 2021; Grieves, 2024; Rogge & Reichardt, 2016). Where sector-coupling theory has advanced multi-vector technical integration (Brown et al., 2018; Wang et al., 2023) and digital twin theory has advanced the model-versus-twin distinction as a threshold for operational intelligence (Wright & Davidson, 2020; Kreuzer et al., 2024), neither literature has formally theorized governance as an endogenous, feedback-responsive subsystem rather than an exogenous constraint. By specifying three explicit feedback loops—operational-to-technological, technological-to-governance, and governance-to-operational—this paper extends existing systems-thinking approaches in energy research (Akrami et al., 2019; Babatunde et al., 2020)

beyond a purely technical flexibility framing toward a tri-domain architecture in which governance adaptivity is modeled with the same structural weight as technological and operational variables. This represents a conceptual departure from additive or layered treatments common in prior sector-coupling and digital twin reviews (Pavičević et al., 2020; Sleiti et al., 2022), and offers a theoretical vocabulary—technology layer, intelligence layer, governance layer, and their interaction dimensions—that subsequent empirical work can operationalize and test.

11.2 Policy Contributions

For policymakers and regulators, the framework's principal contribution is the reframing of governance as a variable to be actively calibrated using digital twin-generated performance data, rather than a fixed regulatory backdrop against which technology deployment is passively evaluated. This has direct implications for capacity-market design, ancillary-service valuation, and de-risking instruments for LDES, which existing scholarship identifies as inadequately calibrated to multi-day and seasonal storage economics (McNamara et al., 2022; Pudjianto & Strbac, 2022). The framework's emphasis on multi-level governance interaction further speaks to persistent regulatory fragmentation documented across federated and multi-jurisdictional contexts (Biresselioglu et al., 2021; Akimov et al., 2023; Michailidis et al., 2025), suggesting that adaptive policy instruments should be designed with explicit provision for jurisdictional customization rather than uniform, one-size-fits-all regulation (Pratama et al., 2022). Additionally, by positioning digital twin transparency as a potential formal input into rate-setting and market-design processes, the framework offers regulators a concrete mechanism—rather than a general aspiration—for closing the data asymmetries frequently cited as a barrier to effective LDES policy (Selänniemi et al., 2025; Chijioke Paul Agupugo et al., 2024).

11.3 Practical Contributions

For system operators, utilities, and technology developers, the framework offers a structured basis for evaluating LDES investment decisions not solely on technology-specific cost curves but on compatibility with digital instrumentation and anticipated governance responsiveness within a given jurisdiction. This addresses a practical gap identified in techno-economic LDES literature, which has tended to evaluate storage technologies in isolation from the operational intelligence systems required to realize their full dispatch value (Guerra et al., 2025; Mantegna et al., 2024). The framework's cross-cutting resilience dimension further offers practitioners a basis for integrating cybersecurity considerations into LDES and digital twin deployment planning from the outset, rather than as a retrofit, consistent with emerging practice recommendations in digital twin cybersecurity research (Sarker et al., 2024; Homaei et al., 2024). Finally, the framework's multi-vector systems orientation offers practical guidance for planners engaged in port, industrial, or regional energy system design, where electricity, heat, and hydrogen infrastructure must be co-planned rather than sequentially deployed (Brækken et al., 2025; Gabrielii et al., 2025).

12. Limitations

This study is subject to several limitations that should inform the interpretation of its contributions. First, as a conceptual and literature-synthesis framework, it has not been empirically validated through quantitative modeling, case comparison, or stakeholder engagement; the research propositions advanced in Section 9.3 remain testable hypotheses rather than confirmed findings. Second, the literature underpinning the framework, while spanning multiple continents and technology domains, is disproportionately weighted toward OECD energy systems and Anglophone-published research, limiting the framework's demonstrated applicability to emerging and developing economies where LDES and digital infrastructure maturity differ substantially (Michailidis et al., 2025; Müller et al., 2020; Obuseh et al., 2025). Third, the digital twin literature drawn upon

for the Intelligence Layer originates substantially from non-energy domains—manufacturing, healthcare, aerospace, and construction (Li et al., 2022; Sadée et al., 2025; Tuhaise et al., 2023)—and its transferability to energy-specific, and particularly LDES-specific, applications has not been empirically demonstrated within the reviewed literature, meaning the framework's Intelligence Layer rests on an extrapolation rather than a directly validated body of energy-sector evidence. Fourth, the feedback-loop architecture specified in Section 7.3, while grounded in the cited literature's constituent findings, is itself an original synthesis rather than an empirically observed mechanism, and its precise functional form (e.g., the strength, lag, or directionality of each feedback relationship) remains unspecified pending future modeling work.

13. Future Research Directions

Building directly on the limitations identified above, four future research directions are proposed. First, quantitative validation of Proposition 1 (technology-intelligence interaction) through dispatch and capacity-expansion modeling that explicitly incorporates digital twin-informed forecasting accuracy as a variable affecting LDES lifecycle cost, extending methodological precedents in existing dispatch studies (Guerra et al., 2025; Mantegna et al., 2024). Second, comparative multi-jurisdictional case analysis testing Proposition 2 (governance-technology interaction), examining LDES deployment rates across jurisdictions with differing degrees of policy adaptivity, building on existing comparative governance methodologies (Biresselioglu et al., 2021; Akimov et al., 2023). Third, development and empirical testing of energy-specific digital twin architectures calibrated to the degradation and cycling profiles of thermal, chemical, and hydrogen-based LDES systems, addressing the domain transferability deficit identified in Section 4.2 (Kobayashi & Alam, 2024; Shiraishi et al., 2024). Fourth, research into the formal integration of digital twin-generated performance transparency into regulatory rate-setting and market-design processes, an integration point not yet addressed in either the digital twin or governance literatures reviewed here (Azizi et al., 2025; Radtke, 2025), including examination of the institutional and legal preconditions required for regulators to accept digital twin data as a formal evidentiary input.

14. Conclusion

This paper has argued that the net-zero power system transition cannot be adequately modeled—technically or institutionally—by treating storage duration, digital intelligence, and governance adaptivity as separate domains of inquiry. Building on independently mature literatures in long-duration energy storage (Albertus et al., 2020; Dowling et al., 2020; Twitchell et al., 2023), digital twin systems science (Grieves, 2024; Fuller et al., 2020; Kreuzer et al., 2024), and adaptive energy governance (Rogge & Reichardt, 2016; Akimov et al., 2023; Radtke, 2025), the paper has identified a compounded, tri-domain research gap at their intersection and proposed a three-layer, feedback-coupled conceptual framework to address it. The framework's central claim is that technology, intelligence, and governance subsystems co-evolve rather than operate sequentially, and that treating any one of them as exogenously fixed—as much of the existing sector-coupling, digital twin, and governance literature implicitly does—constrains both the technical accuracy and the practical utility of net-zero transition planning. The contribution advanced here is deliberately positioned as conceptual and foundational rather than empirically conclusive: its research propositions are offered as a structured agenda for subsequent quantitative modeling, comparative governance analysis, and energy-specific digital twin development, rather than as validated findings in themselves. As net-zero commitments move from legislative targets toward operational implementation, the central proposition of this paper is that their feasibility will depend not on any single technological breakthrough beyond lithium-ion storage, but on the deliberate, structural integration of storage technology, digital operational intelligence, and adaptive governance as co-determining elements of a single systems architecture.

15. Declaration of the Use of Artificial Intelligence

(AI) The authors used Claude AI during the preparation of this conceptual article to support language editing, drafting, and manuscript structuring. The AI tool was used exclusively to improve the presentation and clarity of the text and did not generate the scholarly concepts, theoretical arguments, critical interpretations, or conclusions of the study. All AI-assisted outputs were critically reviewed, substantially revised where necessary, and approved by the authors, who accept full responsibility for the content and integrity of the manuscript.

16. Declarations

The author declares that there are no conflicts of interest regarding the publication of this paper.

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