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An Interoperable User-Centred Digital Twin Framework for Sustainable Energy System Management

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Abstract

This paper presents an Interoperable User-Centred Digital Twin (I-UCDT) framework for sustainable energy system management, addressing the growing complexity of energy generation, storage, demand, and grid interaction across industrial and community-scale systems. The proposed framework provides a unified environment for the visual representation and management of interconnected energy components, supporting informed decision-making among diverse stakeholder groups. The I-UCDT framework adopts a modular plug-and-play architecture based on the Functional Mock-up Interface (FMI) standard, enabling scalable and interoperable integration of heterogeneous energy models from platforms such as Modelica, MATLAB/Simulink, and EnergyPlus. A standardised data layer processes and structures raw model inputs, while an interactive visualisation layer translates complex energy flows into intuitive, user-accessible insights. By applying human–computer interaction principles, the framework reduces cognitive load and enables users with varying technical backgrounds to explore supply–demand balancing, decarbonisation pathways, and optimisation strategies. It supports the full lifecycle of energy system design, planning, and operation, offering flexibility for both industrial and community-scale applications. A case study demonstrates the framework's potential to enhance transparency, usability, and energy efficiency. Overall, this work advances digital twin research for energy systems by combining technical interoperability with explicitly formalised user-centred design characteristics (C1–C10) to promote flexible and sustainable energy system management.

Keywords: energy systems; digital twins; user-centred design; Functional Mock-up Interface; interoperable; black-box Model

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1. Introduction

Digital twins (DTs) [1] are increasingly recognised as powerful tools for managing and optimising complex energy systems, as they provide dynamic, real-time virtual representations of physical assets through continuous bi-directional data exchange [2,3]. By integrating simulation, monitoring, optimisation, and predictive capabilities, DTs enable improved operational performance and support informed strategic decision-making across industrial and community-scale energy infrastructures [2,4].

Despite this growing potential, many existing digital twin implementations remain rigid, model-centred, and problem-specific, offering limited flexibility, scalability, and intuitive user interaction [5]. Such limitations reduce accessibility for non-expert stakeholders

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and hinder adoption across organisational and disciplinary boundaries [6]. Consequently, digital twins are often deployed primarily as advanced simulation tools rather than as inclusive, interactive decision-support environments. Although prior research has explored the integration of process and energy models, significant challenges remain in developing standardised interface designs that simultaneously support interoperability, usability, and effective visualisation of system behaviour [7].

To address these challenges, this study proposes an Interoperable User-Centred Digital Twin (I-UCDT) framework that combines computational rigour with transparency and usability [8]. The framework adopts a modular black-box architecture that enables independent subsystem operation while ensuring standardised communication through protocols consistent with the Functional Mock-up Interface (FMI) standard [9]. This architectural approach supports tool-independent model integration and facilitates compatibility with widely used energy modelling environments such as Modelica, MATLAB/Simulink, and EnergyPlus, thereby enabling flexible and extensible energy system modelling. Beyond its technical architecture, the I-UCDT framework explicitly integrates user-centred design principles to enhance interaction clarity, cognitive accessibility, and system responsiveness. Within an intuitive graphical environment, users can visually construct and explore energy system models, receive real-time feedback, and perform scenario-based analyses. This emphasis on usability aims to bridge the gap between advanced computational models and the practical decision-making needs of diverse stakeholders.

Based on the identified limitations of existing energy digital twin frameworks, this study is guided by the following research questions:

- RQ1: How can interoperability standards such as FMI be combined with user-centred design principles to support flexible and accessible digital twins for energy systems?
- RQ2: What architectural characteristics are required to decouple backend energy model execution from frontend user interaction while maintaining computational rigour and scalability?
- RQ3: How can a user-centred digital twin framework support diverse stakeholder needs across energy system design, planning, and operational phases?

By addressing these research questions, this work establishes a conceptual and architectural foundation for scalable, interoperable, and user-centred digital twin platforms for sustainable energy management. Future work will focus on implementing a functional prototype of the I-UCDT framework, integrating Functional Mock-up Units (FMUs) [9], and conducting systematic usability and interoperability evaluations.

2. Background and Related Work

This section reviews the background and relevant literature that inform the development of the proposed Interoperable User-Centred Digital Twin (I-UCDT) framework. It synthesises key challenges in energy digital twin frameworks and user interaction and concludes by identifying the research gap addressed in this study.

2.1. Background: Energy Modelling and System Challenges

Energy models play a central role in analysing modern energy systems by enabling researchers and decision-makers to examine supply–demand balance, assess policy impacts, and explore "what-if" scenarios that inform future energy transitions [10,11]. Despite their methodological diversity, these models share a common goal: to support informed decision-making across scales, from short-term operational planning to long-term strategies for decarbonisation, efficiency, and renewable energy integration.

Differences among energy models arise from choices in methodology, analytical perspective, temporal horizon, spatial scale, and application context, all of which shape both

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model behaviour and the insights produced. Broadly, models can be distinguished by their analytical approach, including simulation, optimisation, accounting, and equilibrium analysis [10,12]. Simulation models are commonly used to explore system behaviour under varying conditions, while optimisation models identify cost or emission-efficient solutions under defined constraints [13–15]. Accounting and equilibrium models complement these approaches by tracing energy flows and analysing market dynamics and policy impacts over longer time horizons.

Model interpretation is further influenced by analytical perspective. Top-down approaches focus on aggregated economic behaviour, whereas bottom-up models emphasise technological detail and process-level representation. Hybrid approaches increasingly combine these perspectives to capture system-wide trends while retaining sufficient technical fidelity, improving the interpretability of energy transition pathways [13].

Temporal and spatial resolution are also critical design considerations. Energy models range from short-term operational analyses to multi-decade transition studies [5,13] and from global or national systems to regional grids, urban districts, and individual industrial facilities. Higher temporal resolution is increasingly required to represent interactions among variable renewable generation, flexible demand, storage, and multiple energy carriers [5,15].

Beyond analytical capability, accessibility and usability strongly influence the adoption of energy models, particularly for non-expert users. While open-source tools enhance transparency and adaptability, they often require substantial programming expertise, whereas commercial platforms tend to offer more refined interfaces at the expense of flexibility and openness [12,14,16]. As a result, many advanced modelling environments remain confined to specialist communities, limiting broader uptake and interdisciplinary collaboration.

To characterise this landscape, a selection of widely used energy modelling tools is analysed and summarised in Table 1.

Table 1. Commonly Used Energy Modelling Tools and Frameworks Classified According to Their Primary Application Area and Interface Type.

Category	Tools/Models	Area	Interface	References
Long-Term Energy System Planning & Optimization Tools	OSeMOSYS [a] / clicSAND v3.0	Research	🟠	[17,18]
	MARKAL/TIMES [b]	Mixed	🟡	[19–21]
	MESSAGE [c]	Mixed	🟠	[20,22,23]
	LEAP v2.5.551.2	Mixed	🟢	[20,24]
	EnergyPLAN v16.1	Mixed	🟢	[20,25]
	Calliope v0.9.1	Research	🟠	[26]
	PLEXOS 11.0	Commercial	🟢	[5,27]
	ficus [d]	Research	🟠	[22]
	oemof [e]	Research	🟠	[22]
	urbs [f]	Research	🟠	[22]
	Switch [g]	Research	🟠	[28]
	EnergyScope v1.0	Research	🟠	[29,30]
	GenX v0.37	Research	🟠	[31]
Techno-Economic, Microgrid & Renewable Integration Tools	HOMER Pro/Grid v3.15	Commercial	🟢	[32]
	iHOGA [h]	Research	🟢	[33]
	Polysun v10.3	Commercial	🟢	[34]
	DER-CAM [i]	Research	🟢	[35]
	RAPSim v1.0	Research	🟢	[36]
	RETScreen [j]	Mixed	🟢	[35]
	SAM 2025.1.15	Mixed	🟢	[37]
Building & Urban Energy Modelling and Simulation Tools	EnergyPlus v24.1	Mixed	🟡	[38]
	TRNSYS v18.0	Commercial	🟢	[38]
	City Energy Analyst (CEA) [k]	Research	🟡	[32,39–42]
	CitySim [l]	Mixed	🟢	[39]
	IDA-ICE [m]	Commercial	🟢	[38]
	ESP-r [n]	Research	🟡	[39]

Table 1. *Cont.*

Category	Tools/Models	Area	Interface	References
Building & Urban Energy Modelling and Simulation Tools	District-ECA [o]	Research	🟢	[41,42]
	SimStadt [p]	Research	🟢	[41]
	TEASER [q]	Research	🟠	[41]
	UMI [r]	Research	🟢	[32,39–42]
	DIgSILENT PowerFactory [s]	Commercial	🟢	[5,43,44]
Power System Analysis, Grid & Network Modelling Tools	GridLAB-D [t]	Mixed	🟠	[5,43,44]
	MATPOWER [u]	Research	🟠	[5,43,44]
	pandapower [v]	Research	🟠	[5,43,44]
	OpenDSS/OpenDSS-G [w]	Mixed	🟡	[5,43,44]
	TransiEnt [x]	Research	🟠	[5]
	Neplan [y]	Commercial	🟢	[5,45]
	NetSim [z]	Commercial	🟢	[5,46]
	COMPOSE [zi]	Research	🟠	[5]
	PyPSA [zii]	Research	🟠	[5,43,44]
Specialized Energy & Environmental Assessment Tools	GEMIS [ziii]	Mixed	🟢	[5,47]
	Termis v2.0.93	Commercial	🟢	[5,47]

Research = academic/experimental/open; Commercial = stable/user-friendly/costly; Mixed = academic origin then matured. 🟢 = full GUI-based; 🟠 = library/script-based; 🟡 = code core with GUI add-ons. [a] https://osemosys.readthedocs.io/en/latest/ (accessed 8 September 2025); [b] https://iea-etsap.org/ (accessed 8 September 2025); [c] https://iiasa.ac.at/models-tools-data/messageix (accessed 10 October 2025); [d] https://ficus.readthedocs.io/ (accessed 12 October 2025); [e] https://oemof.org/ (accessed 12 October 2025); [f] https://urbs.readthedocs.io/en/latest/ (accessed 12 October 2025); [g] https://switch-model.org/ (accessed 15 October 2025); [h] https://ihoga.unizar.es/ (accessed 15 October 2025); [i] https://gridintegration.lbl.gov/der-cam (accessed 18 October 2025); [j] https://retscreen.net/ (accessed 18 October 2025); [k] https://cityenergyanalyst.com/ (accessed 20 October 2025); [l] https://citysim.epfl.ch/ (accessed 20 October 2025); [m] https://www.equa.se/en/ida-ice (accessed 20 October 2025); [n] https://www.esru.strath.ac.uk/Programs/ESP-r.htm (accessed 21 October 2025); [o] https://www.district-eca.com/ (accessed 21 October 2025); [p] https://www.simstadt.eu/ (accessed 21 October 2025); [q] https://ebc-tools.eonerc.rwth-aachen.de/en/teaser (accessed 22 October 2025); [r] https://umidocs.readthedocs.io/en/latest/ (accessed 22 October 2025); [s] https://www.digsilent.de/en/powerfactory.html (accessed 22 October 2025); [t] https://www.gridlabd.org/ (accessed 23 October 2025); [u] https://matpower.org/ (accessed 23 October 2025); [v] https://www.pandapower.org/ (accessed 23 October 2025); [w] https://sourceforge.net/projects/electricdss/ (accessed 24 October 2025); [x] https://www.tuhh.de/transient-ee/welcome (accessed 24 October 2025); [y] https://www.neplan.ch/ (accessed 24 October 2025); [z] https://www.vitec-energy.com/netsim-grid-simulation (accessed 25 October 2025); [zi] https://reselplan-toolbox.eu/get-started/index.html (accessed 25 October 2025); [zii] https://pypsa.org/ (accessed 25 October 2025); [ziii] https://iinas.org/arbeit/gemis/ (accessed 26 October 2025).

Table 1 classifies commonly used energy modelling tools according to application domain, development maturity, and interface type. The comparison highlights a persistent interface gap: while commercial platforms often provide mature graphical interfaces, many research-oriented and open-source tools rely on script-based interaction or offer only limited graphical support [12,14,16]. This reflects an ongoing trade-off between analytical flexibility and user accessibility. Tools that prioritise transparency and extensibility typically require advanced programming expertise, whereas platforms with refined interfaces often limit model openness. As a result, advanced energy modelling environments remain largely accessible only to expert users.

At the same time, energy systems are becoming increasingly interconnected, with strong coupling between electrical networks, thermal systems, storage, flexible demand, and distributed renewable generation [48,49]. Although recent studies propose advanced optimisation strategies for integrated energy systems [50], many existing modelling environments remain rigid and difficult to adapt, limiting their ability to represent evolving real-world configurations.

Overall, the background analysis indicates that the absence of standardised and user-centred interfaces constitutes a structural limitation across contemporary energy modelling tools, rather than a shortcoming of individual platforms. As energy systems become increasingly interconnected and model complexity continues to grow, this limitation constraints both interoperability and effective stakeholder engagement. These observations motivate the need for interoperable digital twin frameworks that preserve computational rigour while enabling intuitive, transparent, and interactive user engagement, directly informing the architectural and design principles of the proposed framework.

2.2. Literature Review: Interoperability and Interface Design in Energy Modelling

This section reviews existing literature on interoperability mechanisms and interface design approaches in energy modelling, with a focus on their implications for scalable, user-centred digital twin frameworks. As energy systems increasingly span multiple domains, including electricity, heat, storage, and flexible demand, the ability to integrate heterogeneous models and tools has become a central requirement in energy modelling and digital twin development. Interoperability and interface design therefore play a critical role in enabling coherent system representation, cross-domain analysis, and effective user interaction.

Within the literature, a persistent challenge in energy modelling is fragmented data exchange and weak interoperability [51], as many tools are developed in isolation using tool-specific data structures and exchange mechanisms. This fragmentation limits cross-domain integration and constrains the effective use of energy models within coherent digital twin and decision-support environments. As energy systems grow in complexity, co-simulation has emerged as a key mechanism for coupling heterogeneous models across multiple physical domains and temporal scales [52].

However, enabling technical coupling between models does not, in itself, guarantee effective system understanding or decision-making. Prior research in systems engineering and interface design emphasises that well-defined, standardised interfaces are essential not only for technical abstraction and decoupling, but also for structuring meaningful user interaction with complex systems [53–55]. Design methodologies such as TRIZ further highlight the need to balance usability, precision, openness, and robustness through deliberate interface design choices [56]. Together, these perspectives suggest that interoperability extends beyond model-to-model connectivity to include effective, intuitive, and transparent user interaction with integrated systems.

In response to the need for technical interoperability, the Functional Mock-up Interface (FMI) has become a widely adopted standard for model exchange and co-simulation, enabling black-box integration, tool independence, and modular composition through encapsulated Functional Mock-up Units (FMUs) [9]. Recent advances, including FMI 3.0, further enhance co-simulation control, data handling, and scalability [57,58]. FMI has been successfully applied in building energy simulation, distributed co-simulation frameworks, and photovoltaic digital twin applications [59–62], demonstrating strong technical interoperability [63].

Nevertheless, most FMI-based implementations primarily focus on co-simulation execution and data exchange, offering limited support for user-centred abstractions related to simulation control, configuration, and visualisation [64]. Consequently, while technical interoperability has seen significant progress, effective support for accessible, transparent, and decision-oriented interaction with interoperable energy models remains limited.

2.3. Digital Twins in Energy Systems

Digital twins represent the next stage in the evolution of energy system modelling by extending conventional simulation approaches through the integration of computational models with real-time data, enabling adaptive and data-driven decision-making. A digital twin connects physical assets with their virtual counterparts through continuous data exchange [65–67], creating a dynamic environment that supports monitoring, analysis, and optimisation across system lifecycles. Recent review studies characterise energy digital twins as application-oriented systems that integrate heterogeneous models, data-driven components, and interoperable architectures to support planning and operational objectives in integrated energy systems [68–70].

Energy digital twins have been applied across a wide range of contexts, including grid stability and contingency analysis [65], microgrid resilience and resource coordination [71,72], predictive maintenance of grid assets and power electronics [73,74], and industrial decarbonisation through flexible system configurations [75,76]. Comprehensive reviews indicate that these applications predominantly focus on monitoring, analysis, optimisation, and energy efficiency, while differing in levels of system integration and operational maturity [68,69]. Advances in sensing technologies, cloud computing infrastructures, hybrid physics–data-driven models, and visualisation tools further demonstrate the scalability and adaptability of digital twins in complex and distributed energy systems [4]. In specific domains such as energy storage, digital twins have also been integrated with graphical user interfaces to support interactive exploration, real-time visualisation, and operational monitoring [77].

Recent research increasingly emphasises the importance of embedding human-centred design principles within digital twin development to enhance usability, transparency, and stakeholder engagement [78]. To support adoption beyond expert users, scholars advocate for consistent frameworks and reference architectures that reduce fragmentation and avoid ad hoc, one-off implementations [7,79]. Nevertheless, review studies highlight that many existing energy digital twins remain predominantly engineer-oriented, with limited emphasis on user interaction and decision-oriented interfaces despite their application-focused intent [68,70]. Within this context, black-box architectural approaches—exposing standardised inputs and outputs while encapsulating internal model complexity—are gaining prominence, enabling interoperability and scalability while allowing simulation, optimisation, and machine learning tools to coexist within unified digital twin ecosystems.

Despite their demonstrated potential, digital twins continue to face persistent challenges related to model management, scalability, data governance, and cybersecurity [80,81]. More recently, citizen-centred and participatory perspectives have been proposed to improve transparency, inclusivity, and decision relevance, particularly for public-facing and community-scale energy applications [82,83]. However, many current implementations still prioritise technical fidelity and computational precision over usability and accessibility for non-expert stakeholders [66,75]. Bridging this gap requires standardised, user-friendly interfaces that preserve analytical rigour while expanding accessibility and interpretability to a broader range of users.

2.4. Research Gap and Motivation

In summary, while energy models offer strong analytical capabilities, their broader impact is constrained by rigid methodologies, limited interoperability, and interfaces that remain accessible primarily to technical experts. Consequently, many existing tools struggle to support transparent and collaborative decision-making across diverse stakeholder groups.

Energy digital twin frameworks have emerged as a promising evolution and have made notable progress in advancing technical interoperability and orchestration across heterogeneous system components [63]. However, these developments remain largely technically driven, with emphasis placed on model integration, execution, and computational performance. In contrast, comparatively limited attention has been given to how users interact with, configure, and interpret interoperable energy digital twins. Although some studies have explored user interaction in energy management contexts, most notably within smart home environments [84], such approaches address constrained interaction scenarios and do not readily generalise to the complexity and multi-stakeholder requirements of industrial energy systems.

These limitations reveal a clear research gap: the absence of interoperable energy digital twin frameworks that combine robust technical interoperability with intuitive, user-centred graphical interfaces. Addressing this gap motivates this research, which aims to advance energy digital twins into adaptable, decision-oriented platforms that support diverse users and evolving system requirements.

2.5. Novelty and Contributions

This study addresses the identified gaps in existing energy digital twin research by proposing an Interoperable User-Centred Digital Twin (I-UCDT) framework that explicitly integrates technical interoperability with user-centred interface design. Unlike conventional approaches that focus primarily on model-to-model integration, the proposed framework emphasises the role of human interaction in enabling effective, transparent, and decision-oriented use of interoperable energy systems. It improves the digital twin's adaptability to future upgrades and enhancements, allowing system evolution to occur without significant disruption to the end-user experience. The key novelties and contributions of this work are as follows:

- This study introduces the concept of user-centred interoperability, extending traditional notions of interoperability beyond technical model coupling to include meaningful, intuitive, and cognitively accessible interaction between different stakeholders and interoperable energy models.
- A structured energy digital twin framework is proposed that combines modular, black-box architectural principles with layered user interaction and visualisation components. This structure enables scalable integration of simulation, optimisation, and data-driven models while preserving usability, transparency, and system interpretability.
- A set of user-centred design characteristics is formalised for the development of energy digital twin interfaces, addressing interaction design, hierarchical abstraction, system configurability, and result interpretation to support effective decision-making by both expert and non-expert stakeholders.

Collectively, these contributions advance energy digital twin frameworks by bridging the gap between technically interoperable energy digital twins and their effective, user-driven application in real-world energy systems, thereby enhancing usability, decision quality, and practical adoption.

3. Methodology

The design is conceptually informed by international standards, including the digital twin framework for manufacturing (ISO 23247) [85] and Human–Computer Interaction guidelines (ISO 9241-210) [86]. These standards are used as high-level guidance to emphasise that digital twin interfaces should be interoperable and user-oriented, supporting usability, consistency, and effective interaction across diverse stakeholders.

Building on the identified research gap in Section 2, this study adopts a user-centred methodology to design and develop a digital twin framework for energy systems that bridges advanced energy modelling capabilities and accessible decision support. The approach combines technical rigour with user-centred design characteristics to create an interactive, interoperable, and scalable platform suitable for diverse user groups.

The study first proposes the architecture, followed by a layered framework design, and then defines a set of user-centred design characteristics to guide the design, evaluation, and iterative refinement of interaction mechanisms across stakeholder roles. Together, these elements provide a coherent methodological pathway that integrates technical interoperability with human centred interaction design.

3.1. *Architecture of the Proposed I-UCDT (Interoperable User-Centred Digital Twins) Framework*

The Interoperable User-Centred Digital Twin (I-UCDT) framework, illustrated in Figure 1, defines an integrated ecosystem that connects physical energy assets, live and contextual data, computational models, and user-centred interfaces.

As shown in Figure 1, the I-UCDT framework comprises four interconnected functional elements (A to D). These elements maintain connectivity between the physical system (A), live data acquisition (B), and data storage (C) and extend into the digital twin environment (D). The digital twin environment includes a black-box interface layer (D1), a model integration layer (D2), and a user-centred interface layer (D3). Together, they establish a coherent flow of information from real-world assets to decision support interfaces. *Physical Assets* are the physical components, such as solar panels, wind turbines, compressors, and thermal storage units equipped with sensors and actuators. These assets are equipped with sensors and actuators that continuously capture operational parameters, including temperature, pressure, energy output, and flow rate. This data forms the empirical foundation of the digital twin. *Live Data* collects real-time and contextual information, such as weather conditions, electricity market prices, carbon intensity signals, demand response events, and system availability. Continuous updating of these inputs ensures that the digital twin remains synchronised with evolving operational and environmental conditions. *Data Storage* provides a central and persistent repository for both operational and contextual data. Incoming data streams are filtered, structured, and stored to support downstream activities, such as trend analysis, forecasting, scenario evaluation, and model calibration. This domain establishes a consistent data foundation that connects live data with computational modelling and decision support.

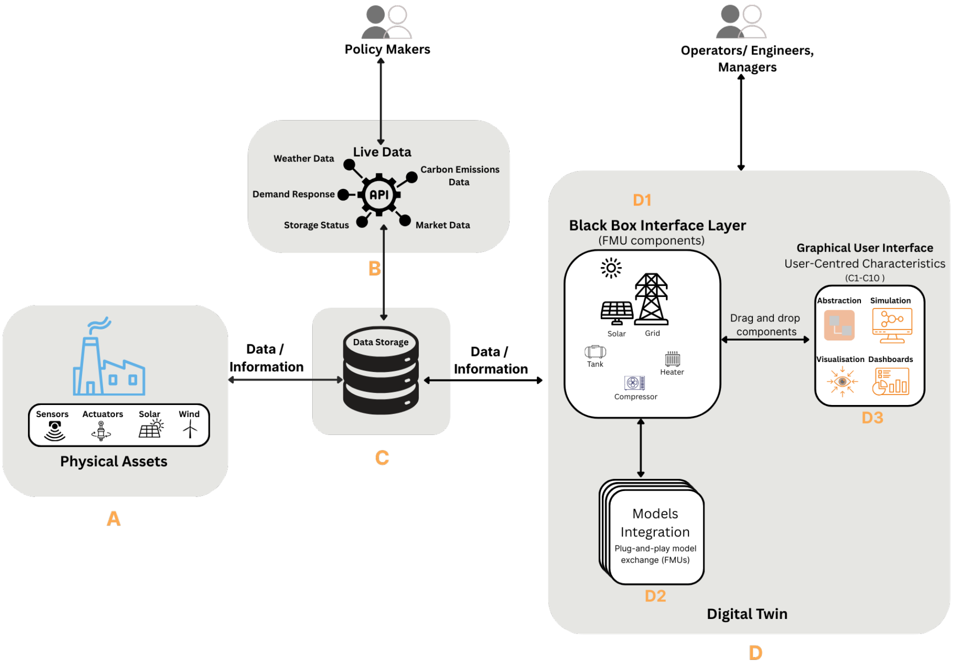

Figure 1. Architecture of the I-UCDT framework for Digital Twins of Energy Systems illustrating five interconnected elements (**A**) physical assets; (**B**) live data integrating external data streams (**C**) central data and information storage and (**D**) the digital twin environment, consisting of FMU components (**D1**), a plug-and-play model integration (**D2**), and a user-centred interface (**D3**).

The *Digital twin* environment, D in Figure 1, consists of three interconnected elements that together enable seamless interaction between models, data, and users. These elements are designed to separate model complexity from user interaction while preserving interoperability and system integrity. The *black-box interface* hosts modular models that function as self-contained entities encapsulated as Functional Mock-up Units (FMUs) compliant with the Functional Mock-up Interface (FMI) standard. Each FMU represents an individual subsystem such as generation, storage, grid interaction, or conversion. FMUs exchange data through predefined variables, allowing them to be combined and reused without exposing internal model formulations [87]. This encapsulation supports modularity, long-term maintainability, and tool independence. The *model integration* manages coupling and co-simulation between FMUs. It governs time synchronisation, data exchange, and coordination across heterogeneous models and tools, enabling hybrid and multi-scale analysis. By separating orchestration from model implementation, the framework allows different modelling approaches to coexist within a single digital twin. The *user-centred interface* serves as the main point of interaction between stakeholders and the digital twin. It is designed based on the user-centred design characteristics (C1–C10) described in Section 3.3. To make the system easier to understand and use, this layer applies hierarchical abstraction, as shown in Figure 2, allowing different users to access information according to their roles. It enables progressive disclosure of system detail without altering the underlying digital twin. At the system level (Level 0), users are presented with aggregated performance indicators to support situational awareness and strategic assessment. At the subsystem level (Level 1), users can explore detailed views of generation, storage, grid interaction, and major loads to support operational analysis and scenario exploration. In this way, a single digital twin instance can effectively support multiple stakeholder roles.

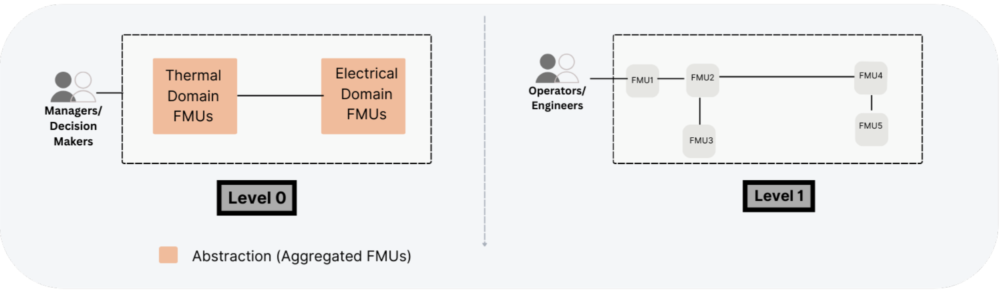

Figure 2. Hierarchical Abstraction of the User-Centred Interface, Illustrating Level 0 (System-Level Aggregated View) and Level 1 (Subsystem-Level Detailed View).

Overall, the I-UCDT framework is user-centred, as it structures interaction around user roles and tasks rather than model complexity. By decoupling model execution from the user interface, different stakeholders can interact with the same digital twin through role-appropriate views. This design supports a continuous feedback loop for simulation, visualisation, and adaptive optimisation, while the adoption of the FMI standard [88] ensures interoperability and scalability across modelling tools and domains.

3.2. Layered Design of the I-UCDT Framework

Building on the I-UCDT architecture shown in Figure 1, the layered framework illustrated in Figure 3 provides a structured representation of the system hierarchy. It is structured as a six-layer pyramid informed by Pyramidal Activity Theory [89], which builds on Activity Theory [90]; it illustrates the flow of information from physical data acquisition to user interaction while maintaining a user-centred orientation across operational levels.

At the foundation, the physical layer represents the energy assets—such as photovoltaic systems, wind turbines, compressors, thermal storage units, and industrial loads—that form the basis of the digital twin. These assets are equipped with sensors and actuators that continuously record key operational parameters, including temperature, power output, flow rate, and pressure. The continuous flow of real-time data from these devices establishes the operational context on which higher layers depend.

The digital layer converts raw sensor data into structured, machine-readable information. It incorporates live data streams from FMUs representing subsystems such as solar, grid, and load components. This layer supports real-time data ingestion, preprocessing, and transformation, ensuring that measurements from the physical domain are readily available for simulation, analysis, and optimisation.

The information layer builds on this by managing data pipelines and contextual enrichment. It aggregates, cleans, and organises both historical and live datasets to support forecasting, trend analysis, and calibration. Through Application Programming Interfaces (APIs), it integrates external data sources such as weather forecasts, demand-response signals, and market datasets, providing a comprehensive understanding of system behaviour.

The service layer encompasses the analytical and optimisation capabilities of the digital twin. It hosts algorithms for performance assessment, cost and emission analysis, and real-time optimisation. Leveraging processed data from the lower layers, it translates complex system dynamics into quantifiable Key Performance Indicators (KPIs)—such as efficiency, emissions, and operating costs—providing essential insights for both operational and strategic decision-making.

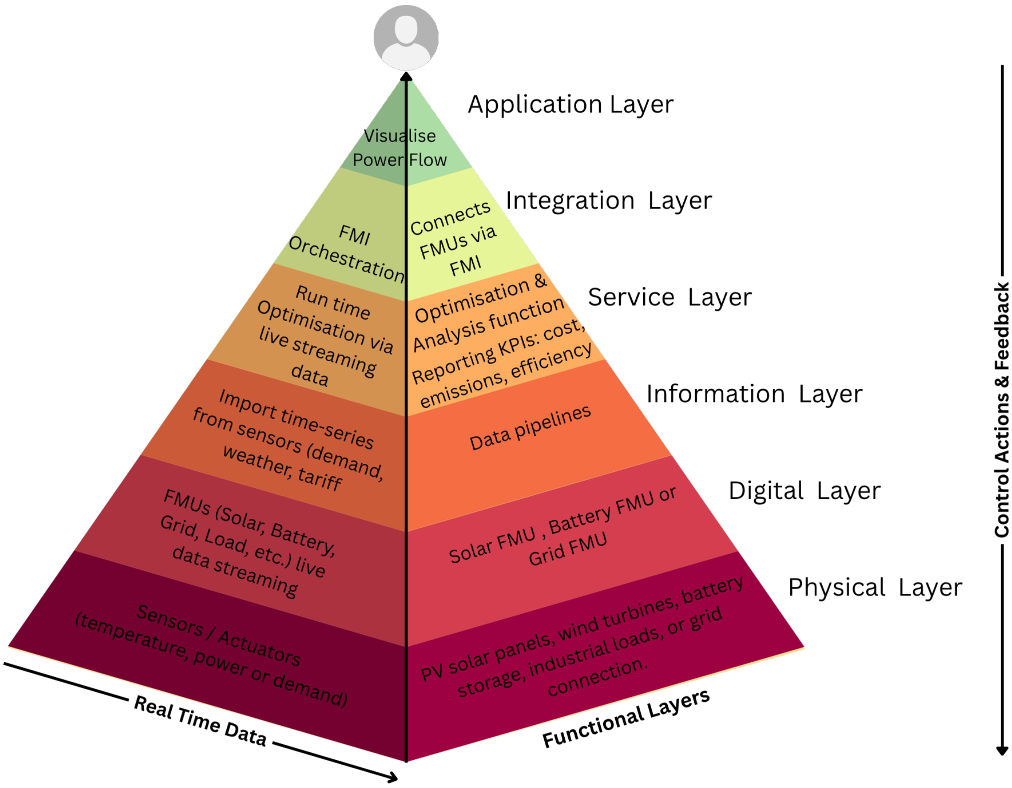

Figure 3. Layered Architecture of the User-Centred Digital Twin Framework Based on PAT (Pyramidal Activity Theory) [89] .

Above this, the integration layer coordinates connectivity among Functional Mock-up Units (FMUs) through the Functional Mock-up Interface (FMI) standard [88]. It manages FMU orchestration, model coupling, and co-simulation across energy modelling platforms, enabling hybrid analysis between physics-based and data-driven models. Acting as a bridge between data and models, this layer ensures consistency and synchronisation across energy simulation environments.

At the apex, the application layer provides the black-box interface that transforms analytical results into accessible, visual formats. Engineers/operators interact through real-time simulations, drag-and-drop modelling tools, and dashboards that visualise energy flows and performance metrics. Decision-makers interact through an abstracted system-level view (Level-0), engaging with summarised indicators such as cost, demand, and carbon intensity. This layer completes the feedback loop by delivering actionable insights that guide both operational adjustments and strategic decisions.

Overall, the layered representation formalises the digital twin's structural hierarchy, illustrating how each layer contributes to creating a responsive, modular, and user-centred system. This configuration not only enhances interoperability and system evolution but also strengthens the framework's ability to support adaptive control and continuous optimisation within complex energy environments. The following section introduces the user-centred design characteristics that will be applied to iteratively improve user interaction with the I-UCDT framework, thereby enhancing usability and promoting energy efficiency.

3.3. User-Centred Design Characteristics for I-UCDT Framework

Digital twin systems are socio-technical artefacts whose effectiveness depends on balancing technical capability with usability and trust [6]. To support this balance, ten user-centred design characteristics (C1–C10) are proposed. These characteristics are grounded in Human–Computer Interaction (HCI) and User-Centred Design (UCD) and are adapted to the requirements of energy system digital twins. They provide a structured basis for assessing whether existing tools can evolve into digital-twin-ready environments that remain technically robust while being accessible to diverse stakeholder groups.

Research on human-centric digital twins [91] and multi-user UCD emphasises the importance of user acceptance, experience, and usability testing in complex interactive systems [92]. These principles build on user-centred systems design [93] and are formalised in ISO 9241-210 [86]. The proposed characteristics are illustrated in Figure 4.

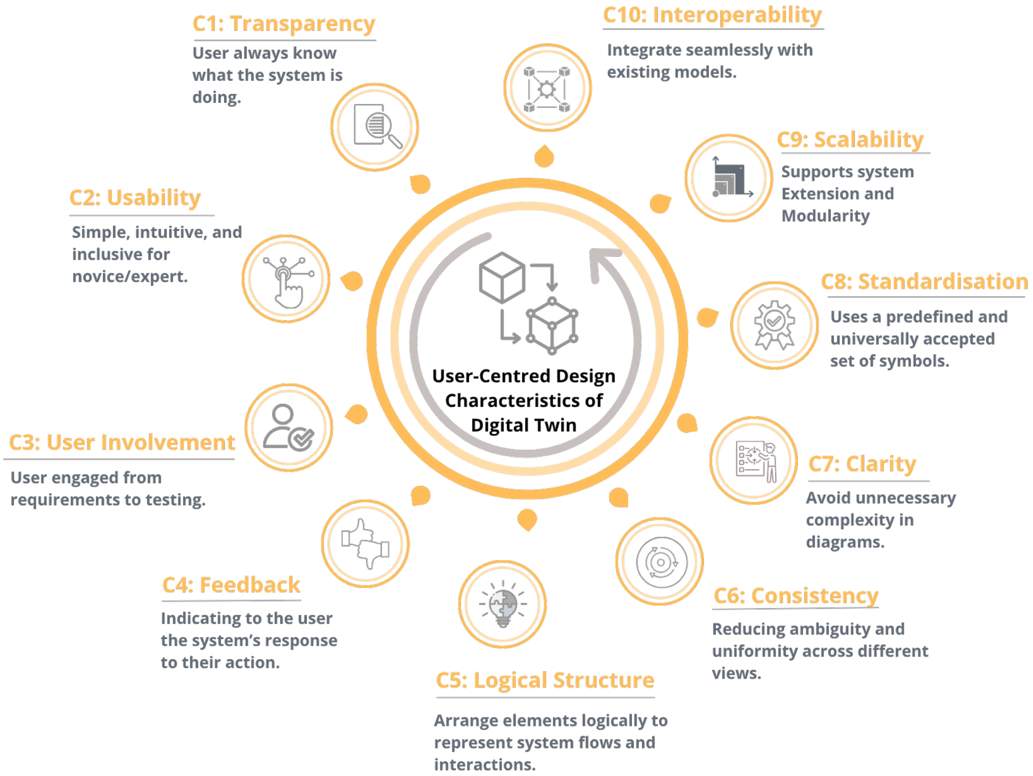

Figure 4. Iterative User-Centred Design Characteristics to Guide the Development of the I-UCDT Framework, with Circular Structures Representing Iterative Development and Feedback.

Transparency and Clarity: Transparency (C1) ensures that users understand how outcomes are generated and why recommendations are made. This fosters trust, supports validation, and aligns with ethical expectations for explainability [94,95]. Closely related, Clarity (C7) focuses on presenting data and model behaviour through intuitive visualisations and well-structured layouts, thereby reducing cognitive effort and supporting informed decision-making [96].

Usability, User Involvement, and Feedback: Usability (C2) and User Involvement (C3) are essential to ensuring that digital twins are not only technically functional but also practical in industrial contexts. Despite significant advances in modelling, many DT interfaces remain difficult to navigate, creating barriers for non-technical users [97]. These characteristics align with established usability standards that emphasise effectiveness, efficiency, and satisfaction in use [86,98]. Embedding participatory design and co-creation practices ensures that systems remain grounded in real-world workflows and user needs [94,99,100]. Feedback (C4) is another fundamental component of effective interaction. DTs must deliver timely, meaningful, and context-aware feedback, enabling operators to act safely and efficiently [6]. Iterative testing and evaluation play a crucial role in refining usability and improving interface quality. This characteristics builds on the long-established importance of feedback in heuristic evaluation [101] and reflects the iterative development cycle central to human-centred design [86].

Logical Structure, Consistency, and Standardisation: As DT systems grow in complexity, the characteristics of Logical Structure (C5), Consistency (C6), and Standardisation (C8) become increasingly significant. Logical structuring of models and interfaces improves comprehension, maintainability, and communication between modules [102]. Consistency in interaction design minimises user errors and supports intuitive learning across different components [94,101]. Standardisation, achieved through frameworks such as the FMI, promotes interoperability and reliability across diverse software environments [97,103].

Scalability and Interoperability: Scalability (C9) and Interoperability (C10) ensure that DT architectures remain adaptable and sustainable over time. Scalable systems can evolve from pilot implementations to large-scale, integrated applications [104]. Interoperability, meanwhile, enables multiple models and services to interact seamlessly, creating ecosystems of connected digital twins that foster collaborative decision-making and shared insights [95,102,103].

Together, these ten characteristics extend user-centred design principles into the digital twin domain. Transparency, usability, involvement, and clarity foster trust and engagement, while feedback, structure, consistency, and standardisation reduce complexity and enhance reliability. Scalability and interoperability support long-term evolution. In the proposed framework, these characteristics are operationalised through hierarchical abstraction in the user-centred interface layer, aligning system-level and subsystem-level views with stakeholder roles. As a result, digital twins can evolve into intuitive, trusted, and human-centred tools that support sustainable energy management and decision-making [86,105,106].

3.4. Summary of the I-UCDT Framework

In summary, the proposed I-UCDT framework integrates structural, interoperable, and user-centred dimensions within energy digital twin systems. The architecture defines the overall system scope and establishes clearly specified interfaces between components, while the layered framework specifies functional responsibilities and supports modular integration of heterogeneous models. Building on this foundation, the user-centred design characteristics provide a systematic basis for the design and evaluation of interfaces, enabling effective interaction across diverse stakeholder roles.

4. Results

The results presented in this section focus on analytical and comparative insights and are structured into two parts: (i) a comparative evaluation of existing energy modelling tools against identified user-centred design characteristics and (ii) the synthesis and evaluation of the I-UCDT architecture in relation to the limitations identified through the comparative analysis of existing frameworks.

4.1. Comparative Evaluation of User-Centred Digital Twin Characteristics

The first result concerns the systematic comparison of existing energy modelling and simulation tools against the ten user-centred digital twin characteristics defined in Section 3.3. Table 2 summarises this evaluation across a broad range of tools, including long-term planning models, techno-economic tools, building and urban simulation platforms, power system analysis tools, and specialised energy assessment software.

Table 2. Comparison of Commonly Used Energy Modelling Tools Against User-Centred Digital Twin Characteristics.

Tool	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**References**
Long-Term Energy System Planning & Optimization Tools											
OSeMOSYS [a] /clicSAND v3.0	✓	✗	✗	✗	~	~	✗	✗	✓	~	[12,14,17,18,107]
MARKAL/TIMES [b]	~	✗	✗	✗	~	~	✗	✗	✓	~	[19,20,108,109]
MESSAGE [c]	~	✗	✗	✗	~	~	✗	✗	✓	~	[20,23,29,108]
LEAP v2.5.551.2	✗	✓	~	~	✓	~	✓	✗	✗	✗	[20,24,110,111]
EnergyPLAN v16.1	~	~	✗	✗	~	~	✗	✗	~	✗	[20,25,29]
Calliope v0.9.1	✓	✗	✗	✗	~	~	✗	✗	✓	✓	[26,107,112]
PLEXOS v11.0	✗	✓	✗	~	✓	✓	✓	✗	~	✗	[27,29,112]
urbs [d]	✓	✗	✗	✗	~	~	✗	✗	✓	✓	[12,107]
Switch [e]	✓	✗	✗	✗	~	~	✗	✗	✓	✓	[28,29,112]
EnergyScope v1.0	~	✗	✗	✗	~	~	✗	✗	~	~	[22,112,113]
GenX v0.37	✓	✗	✗	✗	~	~	✗	✗	✓	✓	[29,31,112]
ficus [f]	✓	✗	✗	✗	~	~	✗	✗	~	✓	[12,107]
oemof [g]	✓	✗	✗	~	~	~	✗	~	✓	✓	[12,14,107,114]
Techno-Economic, Microgrid & Renewable Integration Tools											
HOMER (Pro/Grid) v3.15	✗	✓	✗	~	✓	✓	✓	✗	✗	✗	[115–118]
iHOGA [h]	~	~	✗	✗	~	~	✗	✗	~	~	[116,117,119]
Polysun v10.3	✗	✓	✗	~	✓	✓	✓	✗	✗	✗	[33,34,120]
DER-CAM [i]	~	✗	✗	✗	~	~	✗	✗	~	~	[110,121,122]
RAPSim v1.0	✓	✗	✗	✗	~	~	✗	✗	~	~	[36,117,120]
RETScreen [j]	✗	~	✗	~	~	~	✓	✗	✗	✗	[33,116,123]
SAM 2025.1.15	✗	✓	~	~	✓	✓	✓	✗	✗	✗	[33,37,120,124]
Building & Urban Energy Modelling and Simulation Tools											
EnergyPlus v24.1	✓	✗	✗	~	✓	~	✗	✗	✓	~	[5,38,59,125]
TRNSYS v18.0	~	~	✗	~	✓	~	✗	✗	~	~	[5,33,38,126]
City Energy Analyst (CEA) [k]	✓	✗	✗	~	✓	~	✗	✗	✓	~	[5,32,127]
CitySim [l]	~	~	✗	~	✓	~	✗	✗	~	~	[32,39,128]
IDA-ICE [m]	✗	~	✗	~	✓	~	✓	✗	✗	✗	[5,38,129]
ESP-r [n]	✓	✗	✗	~	~	~	✗	✗	~	~	[32,39,130]
SimStadt [o]	~	✗	✗	✗	~	~	✗	✗	~	~	[5,39,131]
TEASER [p]	~	✗	✗	✗	~	~	✗	✗	~	~	[5,39,42,132]
UMI [q]	~	✗	✗	✗	~	~	✗	✗	~	~	[32,39]
Power System Analysis, Grid & Network Modelling Tools											
GridLAB-D [r]	✓	✗	✗	~	~	~	✗	✗	✓	~	[133–135]
MATPOWER [s]	✓	✗	✗	✗	~	~	✗	✗	✓	~	[112,134,136]
pandapower [t]	✓	✗	✗	~	~	~	✗	✗	✓	✓	[107,112,137]
OpenDSS/OpenDSS-G [u]	✓	✗	✗	~	~	~	✗	✗	✓	~	[134,135,138]
PyPSA [v]	✓	✗	✗	~	~	~	✗	~	✓	✓	[14,107,112,139]
TransiEnt [w]	✓	✗	✗	~	✓	✓	✗	~	✓	✓	[43,140,141]

Table 2. *Cont.*

Tool	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	References
Specialized Energy & Environmental Assessment Tools											
GEMIS [x]	✓	✗	✗	✗	~	~	✗	✗	~	~	[5,39,142]
MODEST	~	✗	✗	✗	~	~	✗	✗	~	~	[5,42,143]
Termis v2.0.93	~	✗	✗	✗	~	~	✗	✗	~	~	[5,42,144]

C1 = Transparency, C2 = Usability, C3 = User Involvement, C4 = Feedback, C5 = Logical Structure, C6 = Consistency, C7 = Clarity, C8 = Standardisation, C9 = Scalability, C10 = Interoperability. ✓ = strong presence; ~ = partial/limited; ✗ = absent or weak. [a] https://osemosys.readthedocs.io/en/latest/ (accessed 8 September 2025); [b] https://iea-etsap.org/ (accessed 8 September 2025); [c] https://iiasa.ac.at/models-tools-data/messageix (accessed 10 October 2025); [d] https://urbs.readthedocs.io/en/latest/ (accessed 12 October 2025); [e] https://switch-model.org/ (accessed 15 October 2025); [f] https://ficus.readthedocs.io/ (accessed 12 October 2025); [g] https://oemof.org/ (accessed 12 October 2025); [h] https://ihoga.unizar.es/ (accessed 15 October 2025); [i] https://gridintegration.lbl.gov/der-cam (accessed 18 October 2025); [j] https://retscreen.net/ (accessed 18 October 2025); [k] https://cea.arch.ethz.ch/ (accessed 18 October 2025); [l] https://www.epfl.ch/labs/leso/transfer/software/citysim/ (accessed 18 October 2025); [m] https://www.equa.se/en/ida-ice (accessed 18 October 2025); [n] https://www.strath.ac.uk/research/energysystemsresearchunit/applications/esp-r/ (accessed 18 October 2025); [o] https://simstadt.hft-stuttgart.de/ (accessed 18 October 2025); [p] https://ebc-tools.eonerc.rwth-aachen.de/en/teaser (accessed 18 October 2025); [q] https://web.mit.edu/sustainabledesignlab/projects/umi/index.html (accessed 18 October 2025); [r] https://www.gridlabd.org/ (accessed 18 October 2025); [s] https://matpower.org/ (accessed 18 October 2025); [t] https://www.pandapower.org/ (accessed 18 October 2025); [u] https://opendss.epri.com/ (accessed 18 October 2025); [v] https://pypsa.org/ (accessed 18 October 2025); [w] https://www.tuhh.de/transient-ee/welcome (accessed 18 October 2025); [x] https://iinas.org/en/work/gemis/ (accessed 18 October 2025).

The comparison reveals several consistent patterns. Most tools demonstrate strong analytical capability and scalability (C9), particularly optimisation-based and power system modelling frameworks. However, transparency (C1), user involvement (C3), and feedback mechanisms (C4) are weak or absent in the majority of cases. Even tools with mature graphical interfaces often lack standardised interoperability (C8) and provide limited support for modular integration with external models.

Only a small subset of tools partially address interoperability through scripting interfaces or bespoke APIs; however, these approaches remain tool-specific and do not support systematic, standards-based co-simulation. Importantly, none of the evaluated tools demonstrate comprehensive coverage across all ten characteristics. This finding indicates that the identified usability and interoperability limitations are structural rather than isolated deficiencies, thereby reinforcing the need for a framework that embeds user-centred principles alongside modular interoperability at the architectural level.

4.2. Synthesis and Evaluation of the I-UCDT Framework

This section synthesises prior energy digital twin frameworks and evaluates them through the lens of the proposed I-UCDT assessment criteria (A1–A6). Table 3 consolidates this comparison across six assessment criteria, User-Centred Design (A1), Simulation and Visualisation (A2), Standardised Graphical User Interface (A3), Interoperability (A4), Scalability (A5), and Multi-Stakeholder Interaction (A6), to highlight the distinctive contributions of the I-UCDT framework.

Building on the comparative evaluation in Table 3, the following synthesis examines how the proposed I-UCDT framework responds to the identified limitations in existing energy digital twin studies.

While prior studies demonstrate strong simulation capabilities, interaction is often limited to expert-driven, script-based workflows with minimal feedback. In response, the I-UCDT framework embeds user-centred design at the application layer (A1) through interactive visualisations and real-time parameter control, enabling active exploration of system behaviour. Simulation and visualisation (A2) are tightly coupled at the application layer, supporting transparent interpretation of energy flows and optimisation outcomes. A standardised, model-independent graphical user interface (A3) abstracts computational complexity, improving usability and consistency across applications. Interoperability and scalability (A4 and A5) are addressed through a modular, layered architecture, as shown in Figure 3, that separates physical assets, digital models, data management, services, and user applications, enabling flexible system expansion without increasing user complexity. Finally, the framework supports multi-stakeholder interaction (A6) through role-appropriate interfaces, enhancing transparency, trust, and shared understanding. Collectively, the synthesis demonstrates that I-UCDT advances energy digital twin design beyond technical optimisation towards a user-centred, decision-oriented framework.

Table 3. Comparative Analysis of Existing Energy Digital Twin Studies Against the I-UCDT Assessment Criteria.

Framework/Study	**Reference**	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
Digital Twin Applications in the Energy Sector	[71]	🟧	🟩	🟥	🟧	🟩	🟧
CoFMPy: A Flexible FMI-based Co-Simulation Framework for Digital Twin Application	[145]	🟥	🟩	🟥	🟩	🟩	🟧
Cyber–Physical Power System Digital Twins—A Study on the State of the Art	[146]	🟧	🟩	🟥	🟧	🟩	🟧
Application-oriented Digital Twin for Integrated Energy System	[70]	🟧	🟩	🟥	🟧	🟧	🟧
Energy digital twin applications: a review	[68]	🟥	🟩	🟥	🟧	🟧	🟧
Analysis of Digital Twin Applications in Energy Efficiency	[69]	🟥	🟩	🟥	🟧	🟧	🟥
Digital Twin Concepts with Uncertainty for Nuclear Power Applications	[147]	🟥	🟧	🟥	🟥	🟧	🟥
Key Problems Related to Integrated Energy Distribution Systems	[134]	🟩	🟧	🟥	🟥	🟧	🟩
Future Power System Digital Twins	[7]	🟧	🟩	🟧	🟩	🟩	🟧
Adaptive Digital Twins for Energy-Intensive Industries	[75]	🟥	🟩	🟥	🟥	🟩	🟧
Digital Twins of Smart Energy Systems	[79]	🟧	🟩	🟥	🟧	🟩	🟧
Design Guideline for a User-Friendly Home Energy-Saving Application	[8]	🟩	🟥	🟧	🟥	🟥	🟩
A Systematic Review of Solar Photovoltaic Energy System Design Modelling framework	[120]	🟥	🟩	🟥	🟩	🟧	🟥
Digital Twin Integration using Lingua Franca and FMI	[148]	🟥	🟩	🟥	🟩	🟧	🟧
Energy Digital Twin Technology for Industrial Energy Management	[2]	🟧	🟩	🟥	🟧	🟩	🟧
Digital Twin for Decision Making in Energy System Design	[149]	🟩	🟩	🟧	🟥	🟧	🟩
Integrating FMI and ML/AI models on the open-source digital twin framework	[150]	🟥	🟩	🟥	🟩	🟩	🟧
Mission profile-based digital twin framework using functional mock-up interfaces	[151]	🟥	🟩	🟥	🟩	🟧	🟥
Generative AI for Sustainable Smart Environments	[152]	🟩	🟧	🟥	🟥	🟩	🟩
The potential of FMI for the development of digital twins for large modular multi-domain systems	[153]	🟥	🟩	🟥	🟩	🟩	🟥
A roadmap to the development of user-centred digital twin	[154]	🟩	🟧	🟧	🟧	🟩	🟩
Digital Twin Framework and Its Application to Power Grid Online Analysis	[65]	🟥	🟩	🟥	🟥	🟩	🟧
COMET: co-simulation of multi-energy systems for energy transition	[155]	🟥	🟩	🟥	🟩	🟧	🟧
I-UCDT Framework	Current	🟩	🟩	🟩	🟩	🟩	🟩

A1: User-Centred Design (UCD); A2: Simulation and Visualisation; A3: Standardised Graphical User Interface; A4: Interoperability; A5: Scalability; A6: Multi-Stakeholder Interaction. 🟩 indicates full coverage, 🟧 partial coverage, and 🟥 no explicit coverage of the assessment criterion.

The layered structure, as shown in Figure 3, improves transparency and system clarity by clearly distinguishing physical assets, digital models, data management, services, integration mechanisms, and user applications. This separation of concerns makes data flows and system behaviour more visible and easier to interpret, which is particularly important for building trust among non-expert and decision-oriented stakeholders.

User involvement and feedback are supported through the application layer, where interactive visualisations and controls allow users to explore system behaviour and observe the effects of changing inputs. This contrasts with many existing tools that rely on script-based interaction and limited feedback, and instead promotes more intuitive engagement with complex energy models.

Interoperability and scalability are addressed through the use of modular components and standard interfaces within the integration layer. By enabling flexible model composition without increasing user complexity, the architecture supports system expansion while maintaining usability. Standardised workflows and interfaces further contribute to consistency and long-term extensibility.

Collectively, the synthesis demonstrates that the I-UCDT framework operationalises transparency and feedback (C1 and C4) through visible data flows, supports usability, user involvement, and clarity via interactive application-level interfaces (C2, C3, and C7), ensures logical structure and consistency through layered separation of concerns (C5 and C6), and enables standardisation, scalability, and interoperability through modular integration mechanisms and standard interfaces (C8–C10).

5. Case Study: Application of the I-UCDT Framework in a Dairy Processing Plant

This section showcases a conceptual case study that applies the proposed I-UCDT framework to an industrial dairy processing plant, illustrating how the framework can be instantiated to support energy system analysis and decision-making.

Dairy processing involves sustained thermal energy demand for evaporation, pasteurisation, and drying operations, together with significant electrical demand from compressors, pumps, and auxiliary equipment. The close coupling between thermal and electrical energy use makes this setting representative of energy-intensive industrial facilities targeted by efficiency and decarbonisation initiatives.

Figure 5 defines the physical and operational boundaries of the industrial plant that underpin the digital twin environment. The physical entity includes equipment associated with evaporation, pasteurisation, and drying processes, instrumented with sensors and actuators that capture steam conditions, thermal demand, electrical loads from compressors and auxiliary systems, and energy flows across the plant. These real-time measurements are transmitted to the virtual entity, where they support simulation, scenario exploration, and analysis. Outputs are then delivered through role-specific user interfaces to provide decision-relevant insights for different stakeholders.

Mapping the case study onto the I-UCDT framework, as shown in Figure 1, reveals four interconnected functional elements (A to D). The physical system (A) captures process heat generation and energy-consuming equipment through measured operational data. Live data acquisition (B) includes solar power production, which contributes to meeting part of the plant's electrical demand. These data streams are structured and synchronised within a central data storage (C), ensuring consistent and time-aligned information for digital twin operation. The digital twin environment (D) provides a modular and user-centred space for simulation and analysis. The black-box interface (D1) maintains a collection of Functional Mock-up Units (FMUs) representing thermal and electrical subsystems. The model integration (D2) supports interoperability by integrating thermal demand profiles generated using the FMI-compliant simulation tool EnergyPlus. Guided by the C1–C10 user-centred design characteristics, as shown in Figure 4, the user-centred interface (D3) aggregates thermal and electrical FMUs to generate role-specific views through hierarchical abstraction.

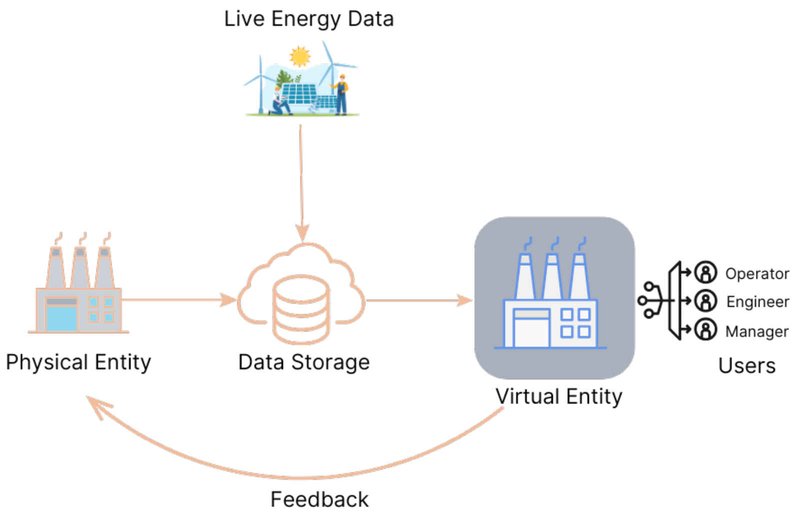

Figure 5. Conceptual Data Flow of the Digital Twin Architecture for Industrial Energy Management.

To further illustrate how the proposed I-UCDT framework is instantiated across its layered architecture, as shown in Figure 3, the instantiation begins at the physical layer, the dairy processing plant's thermally intensive processes and electrical subsystems, monitored through distributed sensors and actuators. At the digital layer, aggregated thermal demand and aggregated electrical demand are instantiated as Functional Mock-up Units (FMUs). The thermal load FMU represents the combined process heat requirements of evaporation and drying, while the electrical load FMU represents auxiliary electricity consumption associated with plant operation. These FMUs encapsulate executable demand behaviour as black boxes with defined inputs and outputs. Operational measurements from the plant are processed through the information layer, where data is structured, validated, and synchronised with contextual inputs such as electricity tariffs, production schedules, and weather-dependent renewable availability. The service layer provides configuring evaporation and drying cycle schedules, selecting and applying electricity tariffs, managing boiler and thermal storage operating modes, integrating weather-dependent renewable generation profiles, and executing energy performance and cost analyses. Coordination between executable FMUs and other system components is handled within the integration layer. Other system components, including boilers, storage systems, grid connections, and renewable generation, are represented digitally to provide physical and operational context rather than as executable FMUs. This modelling choice preserves interoperability while keeping computational focus on decision-relevant behaviour.

Interaction with the digital twin is mediated through the application layer and structured according to stakeholder roles. Operators engage with detailed visualisations that expose process heat demand and electrical load behaviour, enabling short-term operational monitoring and analysis. In contrast, managers and decision-makers are provided with aggregated views that summarise thermal and electrical energy use, associated costs, and carbon intensity. This role-based separation of interaction supports user-centred decision-making while shielding users from underlying technical model complexity. To further manage system complexity and reduce cognitive load, hierarchical abstraction is implemented within the application layer, as illustrated in Figure 6. At Level 0, the interface presents a high-level, aggregated overview of the dairy plant's thermal and electrical energy domains, showing the relationships between energy sources, conversion processes, storage, and demand. At Level 1, the same FMI-orchestrated FMU network is exposed with increased visual and structural detail, allowing users to explore interactions such as the impact of drying-cycle thermal demand variations on electrical consumption and peak loads. Importantly, these abstraction levels differ only in their visual representation, while the underlying model execution remains unchanged.

Within the same layer, the C1–C10 user-centred design characteristics are operationalised. Table 4 summarises how these characteristics are mapped to the framework capabilities using the example of a dairy processing plant.

Although the focus of this case study is a single industrial facility, the same framework structure can be extended to support coordination across multiple facilities or integration with broader energy systems. Figure 7 illustrates this conceptual multi-scale extension, showing how consistent FMU encapsulation, data standards, and interface logic allow industrial, community, regional, and national energy systems to be represented within a unified architecture.

Overall, it illustrates the proposed I-UCDT framework within a real-world dairy processing context. It improves the digital twin's adaptability to future upgrades and enhancements, allowing system evolution to occur without significant disruption to end-user experience.

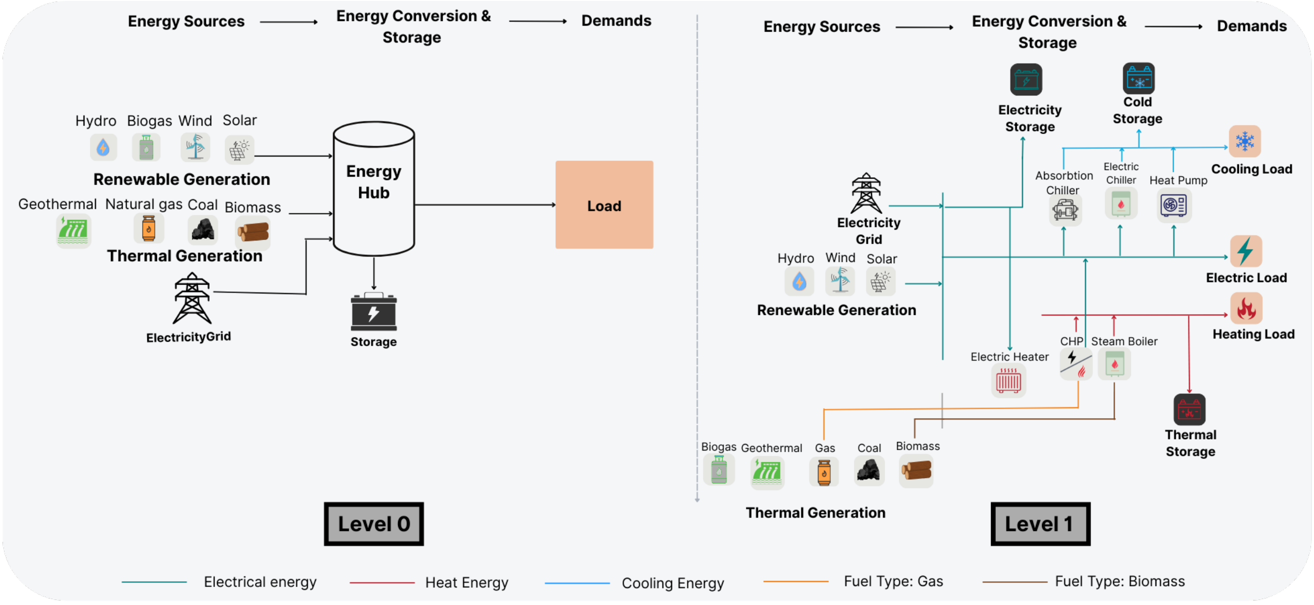

Figure 6. Hierarchical Abstraction of the Plant, Providing Role-Specific Views for Managers (Level 0) and Operators (Level 1) with Arrows Indicating the Flow Direction and Type of Energy.

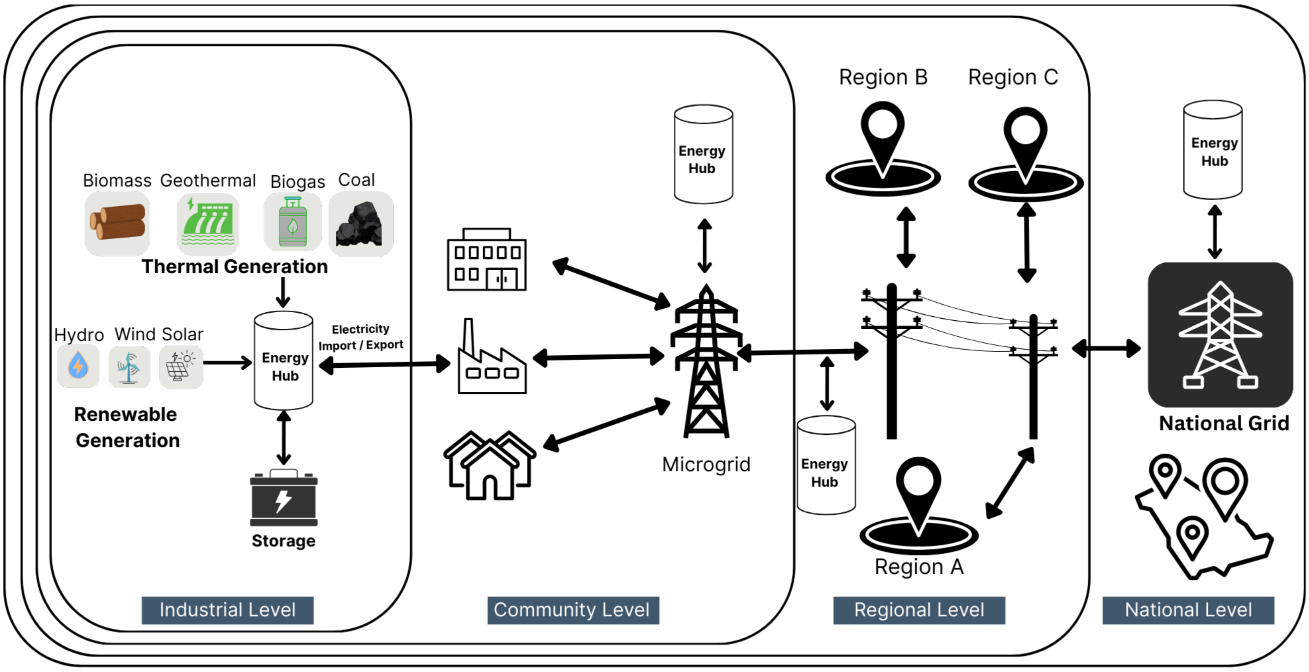

Figure 7. Multi-Scale Energy System Illustrating the Digital Twin's Interaction across Industrial, Community, Regional, and National Energy Levels with Arrows Indicating Energy Import / Export.

Table 4. Framework Capabilities Validated through User-Centred Design Characteristics (C1–C10) in the Dairy Processing Plant.

Characteristic	Framework Capabilities
C1—Transparency	Real-time visualisation of thermal and electrical energy flows, boiler operation, and subsystem performance, with explicit input–output links between physical measurements and digital twin outputs
C2—Usability	Role-specific dashboards support operators in monitoring boilers, loads, and energy use, while managers access aggregated cost and emission indicators without interacting with model internals

Table 4. *Cont.*

Characteristic	Framework Capabilities
C3—User Involvement	Users interact with the system through scenario-based exploration, including adjustment of boiler operation, production schedules, and renewable energy utilisation
C4—Feedback	Dashboards provide immediate feedback by updating energy cost, efficiency, and carbon intensity indicators in response to operational changes
C5—Logical Structure	The interface enables drag-and-drop configuration of dairy plant energy components, supporting intuitive understanding of interactions between thermal and electrical subsystems.
C6—Consistency	Consistent interface layout, colour coding, and interaction logic are applied across thermal and electrical domains and across abstraction levels
C7—Clarity	Hierarchical abstraction provides Level 0 plant-wide energy overviews and Level 1 subsystem-level views, such as boiler–thermal load interactions
C8—Standardisation	Dairy plant subsystems are represented as FMI-compliant FMUs, enabling standardised data exchange and model execution
C9—Scalability	Modular FMU-based representation allows additional processing units, renewable sources, or storage systems to be incorporated without redesign
C10—Interoperability	Thermal and electrical subsystems, including boilers, loads, grid interaction, and renewables, are coordinated through black-box FMU orchestration within a single digital twin

6. Discussion

Earlier digital twin architectures developed within Industry 4.0 and cyber–physical production systems primarily focused on automation, connectivity, and process control, enabled by advances in information and communication technologies [156]. While these approaches strengthen technical integration, reviews of energy digital twin applications show that human interaction and decision-oriented abstraction are often underrepresented, limiting accessibility for non-expert stakeholders [68,69].

To address interoperability challenges, several frameworks adopt the FMI to enable modular and tool-independent model integration [157]. Application-oriented digital twins for integrated energy systems and co-simulation frameworks such as COMET demonstrate the effectiveness of this approach for coordinating multi-energy domains [70,155]. However, these frameworks primarily emphasise model execution and coordination, with limited support for user-centred interaction, abstraction, and decision-oriented visualisation.

User-centred digital twin approaches highlight the value of interactive visualisation and feedback for improving system understanding [154]. Yet such efforts are often confined to interface-level enhancements and lack integration with architectural design. The proposed I-UCDT framework addresses this gap by embedding user-centred design principles across all architectural layers, ensuring that usability, transparency, and interaction guide both system structure and operation.

The comparative evaluation results show that this integrated approach leads to more balanced performance across user-centred design, simulation and visualisation, interface standardisation, interoperability, scalability, and multi-stakeholder interaction. Rather than excelling in isolated dimensions, the I-UCDT framework demonstrates that combining standardised FMI-based interoperability with layered, role-aware interaction is critical for transforming digital twins into effective decision-support environments.

The industrial dairy processing case study illustrates the practical implications of this design. Hierarchical abstraction enables progressive disclosure of system complexity, allowing operators to work with detailed subsystem-level views while decision-makers engage with aggregated system-level indicators. This alignment between system intelligence and human understanding enhances transparency, clarity, and engagement, supporting more informed and sustainable energy management decisions [149,158].

RQ1 is addressed through the proposed FMI-based modular architecture (Section 3.1), in combination with user-centred design characteristics (Section 3.3) and the comparative framework synthesis (Section 4.2). Together, these elements demonstrate how interoperability and usability can be integrated within a unified digital twin design. RQ2 is addressed through the layered separation between FMU-based model execution and the application-layer interface (Section 3.2), illustrating how backend execution can be decoupled from frontend interaction while maintaining scalability and computational rigour. RQ3 is addressed through hierarchical abstraction and role-specific interaction, as illustrated in Figure 2 and described in Section 3.1, demonstrating how the framework supports diverse stakeholder needs across design, planning, and operational phases.

Future work will focus on developing a functional prototype, integrating live operational data, and conducting quantitative evaluations of usability, interoperability, and decision-support effectiveness. These steps will enable further validation of the I-UCDT framework and support its application across a wider range of industrial and multi-energy system contexts.

7. Conclusions

A critical gap in current energy Digital Twin (DT) research and practice is addressed in this study: the persistent disconnect between advanced modelling capabilities and user-centred, decision-oriented interaction. Through a systematic comparison of widely used energy modelling tools and existing DT frameworks, fragmented interoperability and limited support for intuitive, decision-oriented interaction were identified. In response, the Interoperable User-Centred Digital Twin (I-UCDT) framework was proposed. By combining a standardised, FMI-based modular architecture with embedded user-centred design characteristics (C1–C10), as described in Section 3.3, the framework establishes a bridge between advanced energy modelling capabilities and accessible decision support for diverse stakeholder groups.

As illustrated in Section 4.2, the comparative evaluation demonstrates that the I-UCDT framework advances beyond existing approaches by achieving more balanced coverage across six assessment criteria: A1—User-Centred Design (UCD); A2—Simulation and Visualisation; A3—Standardised Graphical User Interface; A4—Interoperability; A5—Scalability; and A6—Multi-Stakeholder Interaction. In particular, systematic co-simulation and model integration are enabled through the use of standardised, black-box FMUs, while progressive disclosure of complexity is supported through hierarchical abstraction and role-specific interfaces. The user-centred design characteristics (C1–C10) play a critical role in shaping the interface, enabling detailed system behaviour to be accessible to expert users while facilitating engagement with aggregated, decision-relevant indicators for decision-makers.

The conceptual dairy processing plant case study illustrates how the proposed framework can be instantiated within an industrial energy management context. The coherent integration of real-time data, FMI-compliant models, and interactive simulation within a single digital twin environment is demonstrated to support operational monitoring, scenario exploration, and strategic decision-making. Cognitive load is reduced through the application of hierarchical abstraction. While the case study is illustrative rather than empirically validated, it confirms the feasibility of operationalising user-centred design principles alongside modular interoperability within a unified energy digital twin architecture.

In addressing the research questions posed in the Introduction, this study demonstrates that interoperability standards can be integrated with user-centred design principles; that back-end model execution based on FMUs can be decoupled from graphical user interaction without compromising computational rigour; and that an energy digital twin framework can support diverse stakeholder needs across energy system design, planning, and operational phases.

Future work will focus on the development of a functional prototype of the I-UCDT framework, followed by iterative usability studies through which the framework will be evaluated and refined. In parallel, external FMUs will be integrated and tested with a wider range of simulation tools to further validate interoperability and usability across diverse modelling environments. Collectively, these efforts will further establish the value of the I-UCDT framework in combining user-centred design with an interoperable system architecture to support informed, transparent, and sustainable energy management.

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Abbreviations

The following abbreviations are used in this manuscript:

DTs	Digital Twins
GUI	Graphical User Interface
PAT	Pyramidal Activity Theory
UCD	User-Centred Design
I-UCDT	Interoperable User-Centred Digital Twin
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
HCI	Human–Computer Interaction
API	Application Programming Interface
MATLAB	MATrix LABoratory
RAMI 4.0	Reference Architectural Model for Industry 4.0
ISO 23247	Digital Twin framework for manufacturing (ISO standard)
IIoT	Industrial Internet of Things
LP	Linear Programming
MILP	Mixed-Integer Linear Programming

NLP	Nonlinear Programming
TRIZ	Theory of Inventive Problem Solving
KPI	Key Performance Indicator
OSeMOSYS	Open-Source energy MOdeling SYStem
TIMES	The Integrated MARKAL-EFOM System
MARKAL	MARKet ALlocation model
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
LEAP	Long-range Energy Alternatives Planning System
EnergyPLAN	EnergyPLAN model (comprehensive energy system analysis)
Calliope	Calliope energy system modeling framework
PLEXOS	PLEXOS Integrated Energy Model
urbs	Urban Energy System Model
Switch	Switch electricity system model
EnergyScope	EnergyScope energy system model
GenX	GenX power system capacity expansion model
HOMER	Hybrid Optimization of Multiple Energy Resources
iHOGA	Improved Hybrid Optimization by Genetic Algorithms
Polysun	Polysun renewable energy design software
DER-CAM	Distributed Energy Resources Customer Adoption Model
RAPSim	Renewable Alternative Power Systems Simulation
RETScreen	RETScreen Clean Energy Management Software
SAM	System Advisor Model
EnergyPlus	EnergyPlus Building Energy Simulation Program
TRNSYS	Transient System Simulation Tool
CEA	City Energy Analyst
CitySim	CitySim urban energy modeling tool
IDA-ICE	IDA Indoor Climate and Energy
ESP-r	Environmental Systems Performance Research software
District-ECA	District Energy Concept Advisor
SimStadt	SimStadt urban energy simulation
TEASER	Tool for Energy Analysis and Simulation for Efficient Retrofit
UMI	Urban Modeling Interface
IDEAS	Integrated District Energy Assessment by Simulation (Python)
GridLAB-D	Grid Laboratory for Distributed Energy Resources
MATPOWER	MATPOWER power system simulation package
pandapower	Python for Power System Analysis
pandapipes	Python for Pipe Network Simulation
OpenDSS	Open Distribution System Simulator
Neplan	Neplan power system analysis software
NetSim	Network Simulation tool
COMPOSE	Comprehensive Power System Simulator
PyPSA	Python for Power System Analysis
TransiEnt	TransiEnt library for energy transition systems
ficus	Ficus energy system optimization framework
oemof	Open Energy Modelling Framework
GEMIS	Global Emission Model for Integrated Systems
MODEST	Model for Optimization of Dynamic Energy Systems with Time-dependent components
Termis	Termis District Heating Simulation Software

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