Energy Storage and Conversion 2026, 4(3), 4414.
doi: https://doi.org/10.59400/esc4414

Review

Renewable energy systems for multi-form coupling: A systematic review of design strategies, energy storage solutions, and future pathways

Shanshan Sun

Beijing Xingcheng Luda Municipal Engineering Co., Ltd., Beijing 102600, China; 18601993723@126.com

CITATION

Sun S. Renewable energy systems for multi-form coupling: A systematic review of design strategies, energy storage solutions, and future pathways. Energy Storage and Conversion. 2026; 4(3): 4414. https://doi.org/10.59400/esc4414

ARTICLE INFO

Received: 19 May 2026
Revised: 21 July 2026
Accepted: 29 July 2026
Available online: 25 August 2026

Abstract: The transition from isolated energy infrastructures to a deeply decarbonised system requires coordinated interaction among electricity, heating, cooling, hydrogen, gaseous fuels, transport, and industrial energy services. This study systematically reviews the renewable energy systems with special emphasis on design and energy storage strategies. The evidence indicates that direct electrification and electricity–heat coupling are generally preferable when conversion efficiency and short- to medium-duration flexibility dominate. In contrast, batteries are most suitable for fast response and intraday balancing. Thermal storage is particularly valuable in heat- and cooling-intensive applications because it can shift demand at comparatively low system cost. At the same time, hydrogen and derivative fuels become more relevant for long-duration, seasonal, industrial, and transport applications in which their infrastructure and conversion penalties are offset by cross-sector value. The review further shows that no modelling method is universally suitable: steady-state optimisation supports strategic planning, dynamic models support control and transient assessment, stochastic and robust approaches address uncertainty, and artificial-intelligence methods require physical constraints, interpretability, cybersecurity safeguards, and field validation. The principal contribution is a common multi-criteria framework based on efficiency, cost, carbon mitigation, infrastructure compatibility, flexibility duration, safety, maturity, and resilience. This framework converts a descriptive technology review into practical guidance for selecting coupling pathways, storage portfolios, and modelling methods under different system conditions.

Keywords: multi-form energy coupling; renewable energy systems; integrated energy systems; energy storage; sector coupling

1. Introduction

Global decarbonization will mean more than just replacing fossil-fuel generation with variable renewable electricity. Solar and wind resources are playing an increasing role in low-carbon energy supply. Mismatches between generation and demand exist over seconds, hours, days and seasons due to the variability, uncertain availability and geographical concentration of these resources. Simultaneously, a large share of the final energy demand remains related to heating, cooling, mobility, industrial processes and chemical feedstocks. Thus, optimization of the electricity sector alone is not able to achieve deep emissions reduction if other energy sectors remain independent or dependent on fossil fuels. The challenge now is to design sustainable energy systems where renewable resources, conversion technologies, networks, storage assets and end-use sectors are coordinated as one functional system. Recent research on renewable integration, integrated energy systems, and carbon mitigation has strengthened the need to consider energy conversion and storage at the whole-system level rather than within isolated technological boundaries [1–4].

It is against this backdrop that the multi-form energy coupling concept has emerged as a significant direction in the journey toward deep decarbonization and the effective use of energy. Multi-form coupled energy systems contrast with traditional systems in that they treat electricity, heating, cooling, gas, hydrogen, and transportation energy as comparatively independent systems, rather than focusing on the coordinated production, conversion, transmission, storage, and consumption of various energy carriers within an integrated system. Renewable energy can be flexibly converted into other sectors using technologies such as combined heat and power, heat pumps, electrolyzers, fuel cells, and Power-to-X routes, thereby increasing the efficiency of the entire system and expanding the area for renewable energy deployment. For example, excess renewable electricity may be converted into heat, hydrogen, or synthetic fuels, and additional flexibility may be added to the thermal and gas networks to handle short-term and seasonal variations. Multi-form coupling, in this meaning, is not merely a technological integration of subsystems, but a redesign of the energy system architecture for greater flexibility, resilience, and carbon efficiency [5–9].

Meanwhile, energy storage is in the middle of making such integrated systems possible. Storage in multi-energy systems based on renewable energy no longer has to rely on electrical batteries to provide short-term balancing. Rather, the widespread array of storage technologies in use, such as electrochemical, thermal, hydrogen-based, mechanical, and chemical storage, is required to enable cross-sector coordination across multiple timescales. Electrical storage with short time scales can fill fluctuations occurring within minutes due to renewable generation; thermal storage can fill the mismatch between power and heating/cooling loads on a daily or hourly basis; and hydrogen or synthetic fuel storage can fill the mismatch on a seasonal basis. Thus, the effectiveness of multi-form coupling systems is largely reliant on the choice of storage technologies, their setup, and their integration with conversion devices and load-side flexibility. A combination of various storage types is emerging as one of the brightest ideas to overcome the time and space constraints of renewable energy [10,11].

There has been significant research on integrated energy systems, sector coupling, energy hubs, hybrid energy storage, and optimization techniques in recent years. Coupling between electricity and heat, enabling the use of hydrogen as a long-duration medium, and the benefits of combining multiple storage technologies in renewable-based systems have been studied. In the meantime, development of modeling, digital control, artificial intelligence and energy management has further increased the opportunities of coordinated planning and real-time functioning of the complex multi-carrier energy networks [12].

Existing reviews have examined integrated energy systems, energy hubs, sector coupling, hydrogen, Power-to-X, batteries, thermal storage, hybrid energy storage, and optimization algorithms in isolation. This literature has constructed important knowledge, but it is fragmented in four ways. First, system architecture and storage selection are often treated as separate topics, when the value of a storage technology depends on the coupling pathway and the service it performs. Secondly, published comparisons often utilise different indicators, boundaries, years and assumptions, making direct ranking difficult and potentially misleading. Thirdly, many reviews list modelling methods without addressing which method is most appropriate for planning, scheduling, control, uncertainty management or resilience analysis. Fourth, sweeping statements about hydrogen, artificial intelligence and advanced Power-to-X systems are not necessarily underpinned by an objective analysis of efficiency losses, infrastructure requirements, safety, maturity, data needs and validation in real-world applications.

This review fills these gaps by developing an integrated decision framework linking system architecture, coupling-pathway selection, storage function, comparative indicators, and modelling-method suitability. Its contribution is not in adding another classification of technology but in developing a common analytical logic to determine when a pathway or storage option is appropriate. The framework evaluates alternatives based on conversion efficiency, annualized system cost, carbon reduction potential, infrastructure compatibility, flexibility duration, response speed, safety, technology maturity, resilience contribution and local resource and demand conditions. It also describes the roles of steady-state, dynamic, stochastic, robust, multi-objective and data-driven models for various decision layers.

The present study aims at determining how renewable multi-form coupling systems should be designed and evaluated for different operational and infrastructural conditions. In particular, the review tackles the architecture variances across buildings, microgrids, industrial parks, districts and regional systems; the coupling pathways selection according to efficiency, cost, decarbonization, infrastructure and flexibility requisites; the electrical, thermal, hydrogen, chemical, mechanical and hybrid storage matching to different timeframes; and the modelling and optimization approaches selection for planning, scheduling, control, uncertainty and resilience issues. The study also identifies limitations of the existing evidence and translates these limitations into specific research and deployment priorities [13,14].

In general, this review aims to provide a better, more integrated understanding of how renewable energy systems can be transformed from isolated applications to highly coordinated, storage-capable, multi-form coupling of renewable infrastructures. It will help academics in their research and assist in practical decision-making for the next generation of low-carbon energy systems by emphasizing collaboration between system design and storage solutions. **Figure 1** presents the analytical relationship among local system conditions, coupling-pathway selection, storage function, network and control constraints, and final performance outcomes. **Figure 1** distinguishes inputs, conversion and storage decisions, operational coordination, and evaluation criteria, while the feedback arrows show that planning and operation must be interactively revised when cost, emissions, reliability, or resilience targets are not satisfied [15–19].

2. Review methodology

The review uses a systematic literature review methodology to ensure that it is comprehensive, reproducible, and has minimal selection bias. A detailed literature review was conducted using four major academic databases: Web of Science Core

Collection, Scopus, IEEE Xplore and ScienceDirect. These databases were chosen to include both energy-specific journals and interdisciplinary engineering journals. The search was performed using combinations of the following keywords: ("multi-form energy coupling" OR "sector coupling" OR "integrated energy systems" OR "energy hub") AND ("renewable energy" OR "renewable integration" OR "decarbonization") AND ("energy storage" OR "hybrid storage" OR "thermal storage" OR "hydrogen storage" OR "battery storage") AND ("design strategy" OR "optimization" OR "planning" OR "scheduling" OR "control architecture").

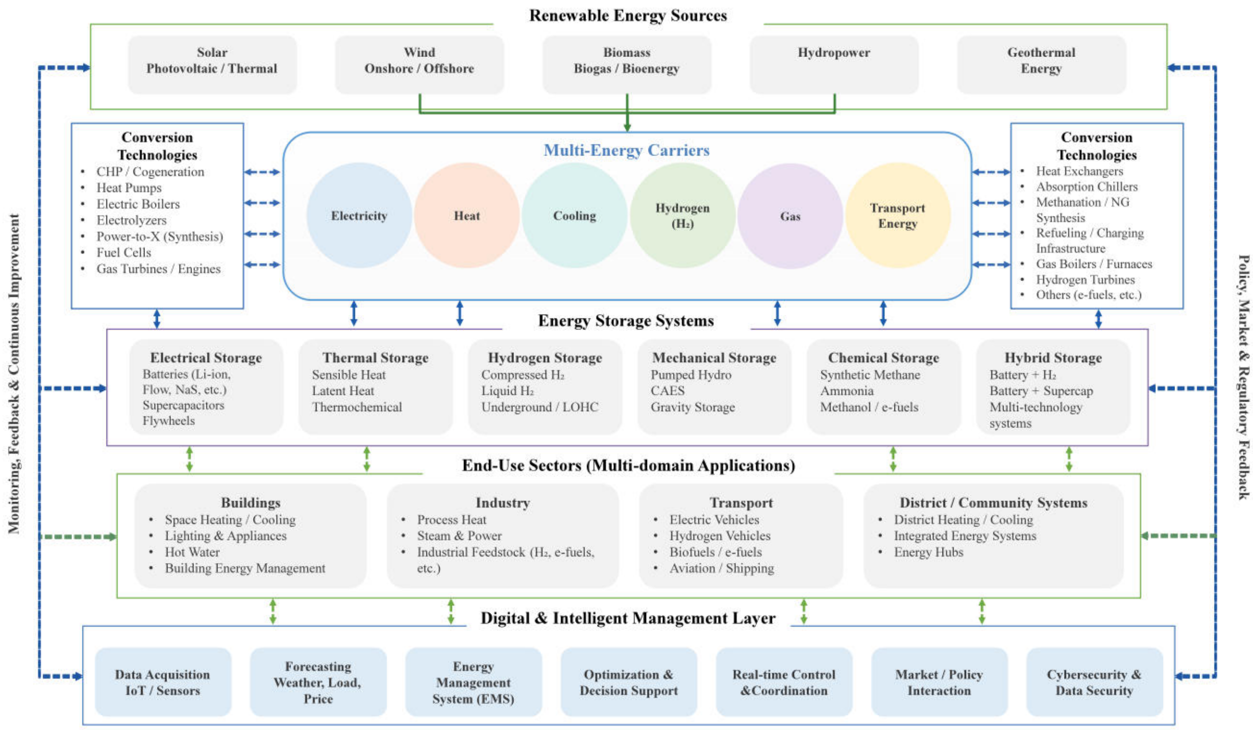

Figure 1. Overall framework of renewable energy systems for multi-form coupling and cross-sector energy interactions.

The search was limited to publications from January 2015 to June 2026 to capture recent developments and provide a sufficient historical perspective. Studies were selected based on the following criteria: (1) multi-form coupling of energy systems, (2) renewable energy integration, (3) storage technologies or design strategies, and (4) peer-reviewed journals or conference proceedings. Studies considering only single energy systems without consideration of coupling or studies without sufficient technical details were excluded.

A two-stage screening process was employed. Relevance was initially evaluated by title and abstract. Second, inclusion criteria were applied to the full-text articles. This resulted in a list of some 380 relevant publications, and 86 key references were selected for detailed analysis according to their contribution to the core themes of the review. The methodological rigour, clarity of results and relevance to the research questions of the selected studies were assessed. The analysis was structured around four thematic pillars: (1) system architecture and coupling pathways; (2) design strategies and planning approaches; (3) storage technologies and their functional roles; and (4) assessment, modelling and optimization methods [20–22].

3. Architecture of renewable energy systems for multi-form coupling

3.1. Conceptual framework of multi-form coupled renewable energy systems

The renewable energy systems architecture of multi-form coupling is fundamentally distinct from that of conventional energy infrastructures, as it is structured around the interrelationship among many energy carriers rather than the individual delivery of a single form of energy. Here, electricity, heat, cooling, gaseous fuels, hydrogen, and mobility energy services are no longer considered distinct subsystems. Instead, they are connected by a network of conversion, storage, transmission, and control processes that enable energy to be converted and moved between sectors based on resource availability and demand. The architectural goal is thus not merely to achieve maximum penetration of renewable energy, but rather to establish a flexible and resilient system in which various energy types complement each other.

One distinguishing characteristic of this architecture is that it has multiple coupling interfaces. Thermal energy can be produced using heat pumps or electric boilers to convert renewable electricity into heat; hydrogen can be generated using electrolysis; and synthetic fuels can be produced via downstream chemical processes. Stored thermal energy, hydrogen, or gaseous fuels, on the other hand, can be converted back into electricity or directly used in end-use industries. This two-way convertibility increases the system's operational degrees of freedom and eliminates reliance on UiPath balancing measures. This has made the design of architecture a question of how to arrange energy pathways in such a way that the temporal fluctuation of renewables is mitigated by cross-sector flexibility as opposed to curtailment or fossil-based backup alone [23].

Multiform coupling can be viewed as a physical and functional architecture in systems terms. The physical layer comprises generation facilities, energy networks, conversion equipment, storage facilities, and loads. The operational layer encompasses the logic of scheduling, the control hierarchy, data exchange, and market or dispatch interfaces. A powerful architecture needs to harmonize the two layers. A system can have many technically possible connections, but unless the connections can be managed in real time or are economically worthwhile, the theoretically possible coupling potential will not be considered in use. This is the reason why the quality of architecture is not defined by the number of attached subsystems, but by the proficiency of these subsystems to be incorporated into a unified energy management system [24].

3.2. Renewable energy sources and core system components

Multi-form coupling systems based on renewable energy typically start with a diversified resource base. In distributed and building-scale systems, solar photovoltaic generation may be the dominant source of electricity, especially when wind power is often overridden in regional or utility-scale systems, since it has a greater generation potential and is complementary in timing. Thermal systems will directly impact the supply of heat and can minimize conversion losses in heating with electricity. The biomass and geothermal are especially useful since they can be used to generate rather dispatchable and relatively stable renewable energy, unlike solar and wind, thus increasing the robustness of architectural structures. Hydropower, when present, serves a special balancing role, providing both renewable energy and flexibility in electricity supply.

Generation units are not the only important elements of the core system. The conversion technologies are critical in renewable energy architecture in coupled systems where they allow integration of the sectors. Combined heat and power (CHP) units are also still applicable to transitional architectures, particularly when they are fed on biomass or low-carbon gases, since they are more efficient in utilizing fuel energy than individual production pathways. The key to electricity-heat coupling is heat pumps as they enhance the useful heat production based on the electrical input and provide an effective pathway of absorbing excess renewable energy. Another vital element is the electrolyzers, which convert the variable renewable electricity into hydrogen which may be stored, transported or utilized in industry and transport. Fuel cells, methanation units, absorption chillers, electric vehicles and flexible loads add more components to the architecture by offering more conversion and demand-side flexibility choices [25–27].

The difference between a designed multi-form coupling architecture and the coexistence of these technologies is not the coexistence itself, but the degree of functional match between the renewable resource profile and the demand structure, and the resources. For example, a municipality with a large winter heating load and abundant wind energy might do well with a different architectural balance than a commercial area with a large summer cooling load and rooftop solar generation. This means that the choice of system components cannot be done based on the availability of technology. Rather, an architectural composition should emerge from a thorough evaluation of time-compatibility, conversion efficiency, infrastructure compatibility, and long-term decarbonization prospects [28].

3.3. Coupling pathways and inter-energy conversion relationships

Multi-form coupling is based on the routes that tie one form of energy to another. Of these, the most mature and economically available one is frequently electricity-heat coupling. Surplus renewable electricity can be diverted to heating demand through heat pumps, electric boilers and resistive heating equipment, and stored in thermal storage to be released back into heating demand later. This route is particularly significant since heating demand often constitutes a significant portion of final energy use, but has traditionally been poorly connected to renewable electricity. The architectural importance of electricity-heat coupling is that it allows the conversion of a hard-to-store form of energy to a more easily buffered form at a lower cost.

The importance of electricity-hydrogen coupling has been getting more and more attention due to its ability to provide a source of long-duration and seasonal balancing. Electrolysis can be used to produce hydrogen, which can be stored, transported, used as a feedstock in industry, or as a synthetic fuel intermediate. This is an architecturally more complicated pathway compared to electricity-heat coupling, as it entails reduced round trip efficiency, and requires more infrastructure. Its value is however clearer when the levels of renewable penetration are high and the balancing of short duration is not adequate and renewable overgeneration is a structurally important aspect. Hydrogen in these situations increases the temporal and sectoral scope of renewable energy that extends beyond the power system [29].

Electricity-gas and electricity-fuel coupling routes also apply in particular in the areas where gas infrastructure already exists. Synthetic methane or other gaseous fuels can be produced in renewable electricity, and are more compatible with the legacy networks and end-use technologies. This may lower transition costs by using existing assets, but it also puts issues on losses associated with conversions, carbon accounting and long term lock-in risks. In architecture, these paths are beneficial when the infrastructural continuity and storage scale are important, but not necessarily appealing in systems that prioritize the maximum direct electrification efficiency.

Coupling electricity cooling and electricity transport takes renewable systems even further. The combination of cooling loads, thermal storage, and demand management can serve as flexible sinks for renewable power. Electrification of transport can create new loads and enable distributed storage resources via vehicle-to-grid or smart-charging strategies. These paths explain a central architectural principle: not only should we add conversion technologies, but we should also redesign the areas of demand in the system into active contributors to the system's balancing [30].

One of the key lessons learned is that not every coupling pathway is equally useful in every situation. Their attractiveness varies based on local loading properties, renewable nature, infrastructure maturity, and policy priorities. Unnecessarily complicated coupling structures can add enormous capital and operational overheads with no commensurate benefits to the system. Thus, the choice of pathways must be motivated by marginal flexibility value rather than by the belief that increased coupling is necessarily accompanied by improved performance. **Table 1** lists the key coupling pathways in renewable multi-form energy systems, the technologies that they enable, key system-level functions, the benefits, constraints, and common applications [30–32].

Table 1. Main coupling pathways, enabling technologies, and system-level functions in renewable multi-form energy systems.

Coupling pathway	Typical input energy form	Typical output energy form	Main enabling technologies	Main system-level function	Major advantages	Main limitations	Typical application scenarios
Electricity–Heat	Renewable electricity	Space heating, domestic hot water, industrial heat	Heat pumps, electric boilers, resistive heaters, thermal storage	Absorption of surplus renewable electricity and thermal load supply	High maturity, strong efficiency in low- and medium-temperature applications, relatively low storage cost	Limited usefulness for long-duration balancing without large thermal demand; reconversion to electricity is inefficient	Buildings, district heating systems, campuses, industrial parks
Electricity–Cooling	Renewable electricity	Cooling energy	Electric chillers, absorption chillers, chilled water storage, ice storage	Flexible cooling production and load shifting	Effective in cooling-dominated regions; compatible with demand response	Strong seasonal and climatic dependence; often site-specific	Commercial buildings, data centers, urban cooling networks
Electricity–Hydrogen	Renewable electricity	Hydrogen	Electrolyzers, hydrogen storage tanks, underground storage, fuel cells	Long-duration storage and cross-sector renewable transfer	Enables seasonal balancing and decarbonization of hard-to-electrify sectors	High conversion losses, infrastructure cost, safety and transport challenges	Industrial hubs, ports, regional energy systems
Electricity–Gas	Renewable electricity	Synthetic methane or gaseous fuel	Electrolyzers, methanation reactors, gas storage, gas network injection systems	Renewable energy conversion into compatible fuel for existing gas infrastructure	Can utilize existing gas networks and large storage capacity	Multi-step conversion reduces overall efficiency; carbon source requirement for methane synthesis	Regions with legacy gas infrastructure, industrial applications

Table 1. *Cont.*

Coupling pathway	Typical input energy form	Typical output energy form	Main enabling technologies	Main system-level function	Major advantages	Main limitations	Typical application scenarios
Electricity–Transport	Renewable electricity	Mobility energy service	Electric vehicle (EV) charging, smart charging systems, vehicle-to-grid platforms, hydrogen refueling systems	Flexible load integration and transport decarbonization	Adds demand-side flexibility and supports renewable utilization	Depends on charging behavior, user acceptance, and infrastructure rollout	Urban transport, logistics hubs, residential mobility systems
Heat–Power	Thermal energy or stored heat	Electricity	CHP, organic Rankine cycle, steam turbines, thermal power blocks	Energy cascade utilization and partial power recovery	Can improve total energy utilization in suitable industrial contexts	Often lower electrical efficiency than direct power pathways; case-specific value	CHP-based systems, industrial waste heat recovery
Hydrogen–Power	Stored hydrogen	Electricity	Fuel cells, hydrogen turbines	Backup electricity supply and long-duration balancing	Useful for strategic reserve and seasonal support	Lower round-trip efficiency than batteries; higher capital intensity	Regional systems, remote microgrids, backup power applications
Multi-pathway Power-to-X	Renewable electricity	Heat, hydrogen, gas, liquid fuels, chemicals	Integrated electrolysis, synthesis units, heat recovery, storage and conversion clusters	Deep sector coupling and full-spectrum renewable utilization	Highest sectoral reach and decarbonization potential	Strong system complexity, investment intensity, and control challenges	Industrial clusters, future integrated energy hubs

3.4. Criteria for selecting coupling pathways

The choice of the coupling path should start with the service requirement and not with a preferred technology. The first question is whether the end use can be directly electrified without unacceptable reinforcement of the network, peak demand, or reliability requirements. Direct electrification is generally preferred where conversion efficiency, fast response and an established electrical infrastructure are important. The attractiveness of electricity-heat coupling is particularly high in cases with significant low- or medium-temperature heat demand, where heat pumps can provide useful thermal output efficiently, and thermal storage can shift demand without reconversion to electricity. Electricity–cooling pathways are equally relevant for cooling-dominated buildings, data centres and district cooling systems with chilled-water or ice storage providing demand flexibility.

Battery storage should generally be prioritised for high-power, short-duration and intraday services such as renewable smoothing, frequency support, peak reduction and local backup. The benefit diminishes when the required energy duration is long, when cycling is infrequent, or when the energy capacity is large relative to the power capacity. Hydrogen is more relevant if the system is characterised by persistent renewable surpluses, multi-day or seasonal imbalances, or demand in industrial, transport, or chemical sectors that can directly use hydrogen. The argument for using hydrogen only for re-conversion to electricity needs to be more convincing, as the whole route involves electrolysis, conditioning, storage, and re-conversion losses. Synthetic methane, ammonia, methanol and other Power-to-X carriers can be chosen when transportability, fuel compatibility, demand for feedstock or use of existing infrastructure is valued higher than maximum round-trip efficiency.

A real project should assess candidate pathways by a multi-criteria process. Efficiency needs to be assessed on the pathway level, not a single device level. Cost should include generation, conversion, storage, networks, replacement, operation, and avoided system costs. The potential for decarbonisation should be calculated against the marginal fuel, life-cycle emissions and fossil fuel service displaced. Infrastructure compatibility should consider existing networks, available space, supply chains, workforce capability and the risk of stranded assets. Flexibility must be defined by response time, discharge time, energy capacity, and the ability to serve more than one sector. Safety and maturity have to be assessed jointly with reliability, resilience, scalability and public acceptance. Hence, the preferred pathway is not necessarily the one with the highest technological complexity but the one that results in the highest system value under local conditions [33,34].

3.5. Structural configurations and system scales

Multi-form, coupled renewable energy systems can be arranged at multiple structural scales with different architectural logics. On the smaller scale, building-level systems combine rooftop solar, heat pumps, batteries, thermal storage, and smart energy control to coordinate electricity, heating, and cooling loads. Their architectural benefit is that they are located close to generation and consumption, hence less transmission is required, and highly responsive control is achievable. But their small scale limits the diversity of resources and their ability to balance over the long term.

Microgrids are a hybrid form in which various distributed resources and loads are synchronized within a localized system. They are able to incorporate electric lighting, heating, cooling, and transportation services whilst retaining partial or complete independence from the primary grid. The beauty of microgrids is that they are flexible and resilient, particularly in remote locations, campuses, and industries. However, their performance is highly contingent on the level of control sophistication and the availability of enough diversity of local loads and renewable resources.

On larger scales, district- and regional-integrated energy systems integrate power networks with district heating, gas infrastructure, hydrogen hubs, and mobility systems. These architectures have the advantage of increased resource pooling, greater diversity in demand patterns, and more opportunities for sector coupling. They have been specifically adapted to industrial parks and urban energy systems, where two or more energy streams are available, and waste heat or common infrastructure may be used. Their drawback is that it increases coordination. As the scale increases, the architecture will need to address network congestion, institutional fragmentation, and the need to optimize various infrastructures that can be owned or controlled independently [35].

There is consequently a major architectural conflict between decentralization and centralization. Decentralized systems improve local independence and might mitigate dependency on transmission, but might not have adequate resources of flexibility or economy. Centralized structures can take advantage of the economies of scale and larger balancing capacity, but they can also be less adaptive and more reliant on big investments in infrastructure. A layered architecture with decentralized, semi-autonomous subsystems is the most promising path forward, though they are also linked to higher-level networks that provide balancing and backup services. This hybrid structuring is indicative of the fact that no single scale can provide the most efficient delivery of all types of flexibility, efficiency and resilience [36,37].

3.6. Energy hubs, network integration, and control-oriented architecture

The energy hub is now a powerful concept to explain multi-form coupling architecture since it offers a convenient abstraction to model the coordination of multiple inputs, outputs and conversion processes at a single node or a subsystem. The electricity, gas, heat, or hydrogen can be included in an energy hub, converted via conversion devices, temporarily stored and then provided as various end-use services. This framework embodies the architectural meaning of the interaction of multiple energies, and is particularly useful in planning and optimization studies. But to put this into practice, the abstract hub models used in practice need to be abandoned in favor of network-aware architectures that account for physical constraints, infrastructure heterogeneity, and dynamic operating conditions.

Integration in networks is thus a key architectural challenge. The power grid, thermal network, gas pipeline system, hydrogen infrastructure and digital communication layer are in contact in a fully coupled renewable energy system. Both networks contain different temporal dynamics and constraints of operation. Electricity systems demand balancing almost in real time; thermal networks are more inertial, and a hydrogen system can facilitate slower yet larger-scale storage and transport capabilities. The success of architecture lies not in harmonizing these heterogeneous dynamics, but in ensuring that all subsystems operate under the same functional logic. This is the reason why the concept of control-oriented architecture has gained significance [29].

Hierarchical coordination is usually adopted in a control-oriented architecture. Local controllers at the device level control individual assets such as batteries, heat pumps, or electrolyzers. At the subsystem level, supervisory control aligns local resources in a building, microgrid, or district. Cross-sector dispatch and infrastructure interaction is influenced at the system level by optimization and market signals. This stratified structure is essential because direct centralized control over all assets becomes rapidly infeasible as the complexity of connections grows. Meanwhile, the complete decentralization of control might not make the most out of the potential of global flexibility. A balanced architecture thus balances local control with coordination at the system level through forecasting, communication, and adaptive scheduling.

Finally, the design of renewable energy systems to facilitate multi-form coupling must not be considered through the lens of technological diversity, but rather through the lens of their ability to convert renewable variability into manageable system flexibility. Simplistic architectures are unable to unlock cross-sector value, whereas complex architectures are prone to inefficiency and operational fragility. The question is how to find configurations in which renewable generation, conversion pathways, storage assets, network infrastructure, and control systems complement each other in a scalable and economically defensible way. The design strategies to be discussed in the following section are based on this architectural view [24,38,39].

4. Design strategies for multi-form coupling systems

4.1. Design objectives and strategic logic

Renewable energy systems design is no longer just a matter of adding renewable generation to existing infrastructure. It necessitates a reconsideration of the structural arrangement of various energy carriers, conversion systems, storage resources, and demand sectors to achieve high efficiency, deep decarbonization, and operational flexibility simultaneously. Here, design strategies should go beyond a single objective, e.g., the minimum cost of capital or the maximum renewable penetration. An effective coupled system should be able to fulfill several and usually competing goals, such as economic feasibility, carbon mitigation, supply resilience, reliability, flexibility, and long-term flexibility.

This multifunctional character is why the design of coupled systems is always more complicated than that of traditional power systems. What seems like a design choice that would be advantageous based on one aspect might prove detrimental to the overall system performance when cross-sector interactions are taken into account. As an illustration, maximizing direct electrification can enhance energy efficiency in the near term, but can also raise peak electricity demand and increase reliance on electric infrastructure if other thermal or hydrogen pathways have not yet been developed. On the other hand, too many conversion paths may cause unnecessary complexity and conversion losses. The main design issue then becomes to find a middle-ground architecture where each subsystem has a specific flexibility role and adds to the overall coherence of the energy system [40–43].

The design process should therefore use a staged decision sequence. The required energy services and flexibility timescales should first be defined, followed by screening of technically feasible coupling routes. Candidate architectures should then be compared using common economic, environmental, operational, infrastructure, maturity, safety, reliability, and resilience criteria. Detailed optimisation should be undertaken only after infeasible or weakly justified pathways have been excluded. This sequence reduces technology-led overdesign and ensures that optimisation improves a defensible architecture rather than compensating for an unsuitable one.

4.2. Planning and capacity configuration

System planning is the first major layer of design strategy, because the long-term configuration of assets determines the operational flexibility available to the system over its lifetime. In renewable multi-form coupling systems, planning typically involves the joint sizing of generation units, conversion technologies, storage devices, and network capacities. Unlike conventional expansion planning, where electricity generation adequacy is often the dominant concern, coupled system planning must consider the interdependence among electricity, heating, cooling, gas, and hydrogen sectors. As a result, planning decisions have greater structural significance, since overinvestment or underinvestment in one subsystem can propagate inefficiencies throughout the entire architecture.

A key design issue is the degree of renewable resource diversification. Combining solar, wind, biomass, geothermal, or hydropower can reduce aggregate variability and improve complementarity across seasons and times of day. However, diversification is not automatically beneficial if it introduces technologies that are expensive, locally unsuitable, or difficult to integrate. Effective planning should therefore distinguish between physical diversity and functional diversity. The former refers to having multiple renewable sources, while the latter refers to the overall system's capacity to respond flexibly to changing operating conditions. In many cases, a system with fewer renewable technologies but stronger coordination of conversion and storage may outperform a more technologically diverse but weakly integrated configuration [44].

Capacity configuration must also account for the role of sector coupling in reducing curtailment and shifting demand. For instance, oversizing renewable electricity generation may be justifiable in systems with robust heat pumps, electrolyzers, thermal storage, or hydrogen storage, because excess power can be redirected rather than wasted. In contrast, the same strategy may be uneconomic in systems lacking downstream flexibility. This highlights a critical insight: optimal renewable capacity cannot be determined independently of conversion and storage design. Capacity planning in coupled systems is therefore relational rather than isolated, and the value of each component depends strongly on the capabilities of the others.

Another important planning question concerns the scale and modularity of infrastructure. Large centralized installations may offer lower unit costs and greater economies of scale, especially for electrolysis, district heating, or industrial waste-heat utilization. Yet modular distributed systems can be deployed incrementally, adapt more easily to local conditions, and enhance resilience through redundancy. A growing body of design thinking suggests that future systems should favour modular architectures embedded within larger coordinated networks. This approach allows capacity to be expanded progressively while preserving interoperability and local flexibility, thereby reducing the risk of stranded assets under uncertain technological and policy futures [45–47].

4.3. Operational scheduling and multi-timescale coordination

When structural potential is determined by planning, its actual realization in practice is through operational scheduling. Multifaceted, renewable coupling systems are highly uncertain because they are subject to changes in renewable generation, demand behavior, market demand, and equipment conditions. Consequently, the scheduling strategies are designed to be central to system performance. The operational scheduling in such systems has to coordinate a set of energy carriers at various scales in time, seconds and minutes to electrical balancing, hours and days to thermal management, and weeks or months to use up hydrogen or seasonal storage.

The best scheduling strategies are those that take advantage of the complementary dynamics of various subsystems. Short-term fluctuations can be accommodated with electrical storage and fast-response devices; intraday mismatches can be accommodated with thermal systems; and long-term balancing can be accommodated with chemical or hydrogen pathways. Temporal layering is a critically important design principle. The system must distribute balancing tasks, rather than placing all demands for flexibility on a single type of resource, based on the speed of response, storage duration, efficiency, and cost of each technology type. This layered approach can minimize redundant cycling of costly assets, maximize the use of less-costly flexibility resources and enhance the efficiency of the entire system [48].

Day-ahead scheduling is important to predict the availability of renewable and load demand but real-time adjustment is also important as forecast errors are inevitable.

Cross-sector dependencies can also amplify the effects of forecast errors in coupled systems. As an illustration, a sudden decrease in renewable energy might not only impact power but heating, hydrogen generation, or charging time. Design strategies should thus incorporate a high-quality mechanism of receding-horizon control, reserve allocation, and uncertainty management. Systems based on overly optimistic predictions or deterministic dispatch models can work well on paper but be easily broken by actual operating conditions.

Another important aspect of the operations design is demand-side coordination. Flexible loads in buildings, industry, transport, and thermal networks can reduce storage and generation loads, provided they are actively scheduled. The worth of demand response, however, would rely on the extent to which it is integrated into the system design. Demand flexibility should not be considered a residual adjustment tool because it is not integral to its structure. Load flexibility is considered an asset of core balancing in well-designed coupled systems, especially in areas such as heating, cooling, and electric mobility, where service delivery can often be deferred without affecting user comfort or productivity [49].

4.4. Control architecture and intelligent energy management

Scheduling of operations is not enough when the control architecture is unable to run the decisions based on a heterogeneous set of devices and infrastructures. Designing of control systems in multi-form coupling environments is particularly difficult due to the differing dynamics, ownership, communication capability and priorities of operation between assets. Other loads, such as batteries, heat pumps, electrolyzers, thermal storage tanks, electric vehicles, and industrial loads, are not responsive to control signals and may not be effectively managed at scale by a central control.

As a result, hierarchical control has gained popularity. Local controllers on the lowest level deal with equipment protection, stability and immediate response. At the intermediate level, subsystem controllers coordinate buildings, microgrids, district heating networks, or hydrogen clusters. At a higher level, there is supervisory optimization, where the allocation of energy across sectors, market participation, and system-wide objectives are handled. This hierarchy is a practical design point: at the local level, there must be speed and reliability, yet at higher levels, there must be coordination to extract system-wide flexibility and prevent conflicting actions among subsystems.

This is a significant trend in current design strategies, as intelligent energy management is becoming a larger part of them, supported by data analytics, forecasting, and artificial intelligence. Predictions of renewable output, demand and equipment behaviour can be enhanced by machine learning techniques, and advanced optimization and reinforcement learning can be useful in adaptive dispatch in uncertain environments. But the worth of prudent management must not be exaggerated. Performance can be improved through data-driven methods, though this does not mean that physical design does not need to be sound. A poorly designed system will not become an optimal one just because its controller is more advanced. Actually, over-reliance on the complexity of the algorithm can hide structural flaws like short storage time, inappropriate choice of coupling, or insufficient network bandwidth [50].

An amalgamation of both physical understanding and digital smarts is thus the most promising design path. Powerful assistance can be offered by digital twins, predictive control frameworks, and cyber-physical coordination platforms, but they must be supported by a clear architecture with well-defined functional roles of each component. A good design should not be made up by intelligent control, but enhanced.

4.5. Flexibility, resilience, and reliability-oriented design

One of the main promises of multi-form coupling is increased flexibility, which cannot be limited to flexibility. High-renewable penetration systems should also be resistant to disturbances and dependable with a broad spectrum of operating conditions. This brings in the other design layer where the system is not only to be tested in normal operation, but also with equipment failure, communication breakdown, extreme weather, supply interruption, and market volatility.

Design oriented to flexibilities emphasizes the capacity to absorb variability and redistribution of energy flows between sectors. Resilience-oriented design goes even further and poses the question of whether the system is able to sustain important services in case of degradation of components of the infrastructure. Practically, the two objectives are similar yet different. A system that is highly optimized and has little redundancy can be flexible in normal situations but can fail in extreme conditions. Alternatively, a more diversified system that stores data in multiple locations and has a local backup might not be as cost optimal when measured in a steady-state analysis but would be much more reliable in practice.

This is essential, especially in multi-form coupling systems that are renewable, since interdependence may turn out to be both strong and weak. Coupling enables one subsystem to support another; however, it may also lead to cascading risks in case failures spread across interfaces. An example of such would be the lack of electricity, which can occur during heat supply in highly electrified buildings, and communication malfunction that can diminish the efficiency of coordinated dispatch. The design strategies should thus incorporate selective redundancy, fail-safe operating modes, islanding where necessary, and an apparent prioritization of critical loads and energy services [51].

Resilience to weather is also emerging as a determining design factor. Extremes associated with climate have the potential of impacting renewable generation, demand intensity, and availability of infrastructure at the same time. The mono-renewable or mono-balancing systems are particularly susceptible to such circumstances. This strengthens the importance of diversity not just in technologies, but also in mechanisms of flexibility and infrastructure routes. A resilient design is one where electrical, thermal, and chemical paths can take the place of each other partially, in the event of abnormal conditions [30]. Reliability in coupled systems in this sense should be construed as an outcome of coordinated diversity as well as individual robustness. It is not the purpose of the design to stiffen all components equally, but to ensure that the system maintains adaptive capacity in the face of stress. **Table 2** shows the key dimensions of the design of multi-form coupling systems, their strategic focus, anticipated benefits, and trade-offs.

Table 2. Design strategies for renewable multi-form coupling systems and their implications.

Design dimension	Main design focus	Strategic considerations	Expected benefits	Main trade-offs or risks	Typical research emphasis
System planning	Long-term configuration of generation, conversion, storage, and networks	Matching renewable resources with demand profile; balancing centralization and decentralization; ensuring modular scalability	Improved structural efficiency and long-term adaptability	Overdesign, stranded assets, poor alignment between infrastructure and actual flexibility needs	Capacity expansion, multi-objective planning
Capacity sizing	Determination of rated capacities for major assets	Coordinated sizing of renewables, storage, conversion units, and flexible demand resources	Reduced curtailment and improved economic performance	Mis-sizing in one subsystem can propagate inefficiencies across the whole system	Techno-economic optimization, scenario analysis
Operational scheduling	Day-ahead and real-time dispatch of multiple energy carriers	Coordination across timescales; treatment of uncertainty; prioritization of low-cost flexibility resources	Better renewable accommodation and lower operating costs	Forecast errors and coupled uncertainty may reduce dispatch quality	Stochastic dispatch, robust scheduling
Demand-side integration	Use of flexible loads as active balancing resources	Shifting of heating, cooling, EV charging, and industrial demand	Lower storage requirement and smoother net load	User comfort, process constraints, and behavioral uncertainty	Demand response modeling, smart load control
Control architecture	Coordination among heterogeneous devices and subsystems	Hierarchical vs. distributed control; communication reliability; local autonomy vs. system-level optimization	More stable operation and better real-time response	Complexity, cybersecurity exposure, interoperability issues	Cyber-physical energy systems, distributed control
Storage coordination	Functional allocation among different storage technologies	Matching response speed, duration, and sectoral role to actual flexibility tasks	Higher whole-system efficiency and reduced asset stress	Poor coordination can cause overlapping functions and low utilization	Hybrid storage management, multi-timescale control
Resilience-oriented design	System performance under disturbance and extreme events	Redundancy, islanding capability, critical load prioritization, fault containment	Improved service continuity and adaptive capacity	Higher upfront cost and possibly lower short-term cost optimality	Resilience metrics, stress testing
Infrastructure integration	Coupling of power, thermal, gas, hydrogen, and digital networks	Interoperability, legacy infrastructure compatibility, data sharing, and ownership coordination	Broader flexibility and more efficient sector integration	Institutional fragmentation and complex governance	Integrated infrastructure planning

4.6. Definitions and measurement of flexibility, resilience, and reliability

In this section, we seek to provide methodological clarity in the assessment of multi-form coupling systems by defining and measuring three important, yet often confused, performance concepts: Flexibility, Resilience, and Reliability.

Flexibility is the capability of the energy system to respond to the variability and uncertainty of supply and demand with an acceptable performance. There are several complementary indicators by which this notion can be measured. The Flexibility Factor (FF) is a holistic metric of system adaptability, defined as the ratio of flexible capacity to net load variability. Systems with $\mathrm{FF} \geq 1.2$ are highly flexible, while systems with $\mathrm{FF} < 0.8$ suffer from severe flexibility constraints. Ramp capability (MW per minute available for quick adjustment) reflects the system's ability to respond to sudden changes. The Curtailment Rate, i.e., the share of renewable energy that is curtailed due to inflexibility, is a direct measure of the efficiency loss caused by a lack of flexibility. Storage Utilization Efficiency is the ratio of the number of storage cycles used to the theoretical storage capacity. It is a measure of how well storage assets are utilized to provide flexibility [52,53].

Resilience is the ability of the system to anticipate, withstand, adapt to, and recover quickly from disruptive events such as extreme weather events, equipment failures and cyber-attacks. The Resilience Index (RI) is a composite measure expressed as a function of the system performance during and after disruption with respect to normal conditions.

$$\begin{aligned} \mathrm{RI} = (&\text{post-disruption performance} \times \text{recovery rate})/ \\ &(\text{normal performance} \times \text{restoration time}) \end{aligned} \tag{1}$$

where higher RI is better in terms of resilience. Recovery Time is an operational measure, quantifying the time to recover to normal operation after a disturbance. The Critical Load Survival Rate, representing the percentage of essential loads that stay online during extreme events, reflects the system's ability to prioritize critical services. Infrastructure redundancy, as measured by the number of alternative pathways for critical services, offers a structural measure of resilience capacity.

Reliability is the ability of the system to provide energy services steadily and without interruption under normal operating conditions. Typical reliability indices are SAIDI (System Average Interruption Duration Index)—average outage duration per customer; SAIFI (System Average Interruption Frequency Index)—average number of outages per customer; LOLE (Loss of Load Expectation)—expected number of hours per year in which supply would be deficient; and ENS (Energy Not Supplied)—total amount of unsatisfied demand in MWh. Typical targets for modern power systems are SAIDI less than two hours per year and LOLE less than 0.1 h per year. However, coupled systems may have relaxed electrical reliability requirements if thermal storage is used to provide backup heating or cooling services.

These three concepts serve different but complementary roles in system design. Flexibility addresses system performance under normal operational uncertainty, targeting the ability to handle renewable variability and demand fluctuations. Resilience is the ability of systems to respond to extreme conditions and to recover from any disruption. Reliability is the ability to maintain system performance under normal circumstances through a strong infrastructure and maintenance. In contrast, a resilient system with built-in redundancy may not appear as cost-optimal in a steady-state analysis but is more robust in practice. A system can be highly reliable and flexible, but still vulnerable if it is not resilient to major disruptions. Understanding these differences is important for a well-balanced system design, as optimization for one criterion without considering the others may lead to performance gaps under different operating conditions [54,55].

4.7. Design implications and emerging directions

Taken together, the above design strategies suggest that multi-form coupling systems based on renewable energy should not be treated as a set of technologies but as a socio-technical infrastructure. Planning, scheduling, control and resilience design are highly interdependent and failures in one layer tend to diminish the value generated in another. The greatest implication is that effective design relies on effective coordination across timeframes, sectors and levels of infrastructure.

There is a developing view that the way forward in design strategies is to take hybrid forms, which involve direct electrification but selective use of thermal, hydrogen and other conversion pathways. These systems have a higher chance of achieving not only efficiency but also profound flexibility compared to architectures built around a single dominant carrier. Concurrently, design should be context-based. The coupling pattern is never optimal, since the relative value of each pathway depends on the endowment of resources, the composition of demand, climatic conditions, infrastructural heritage, and the policy regime [24].

Finally, the design aspect of multi-form coupling systems is to be evaluated based on the capacity to convert renewable variability into a limitation into a flexibility source that can be managed and economically utilized. To do so, it takes not only a high level of optimization and intelligent control, but also rigorous architectural decisions that align technology roles with the actual system requirements. Based on that, the next design aspect that is considered necessary is energy storage, which is discussed in the following section.

5. Energy storage technologies and their roles in coupled systems

5.1. Storage as a structural enabler of multi-form coupling

Multi-form coupled renewable energy systems place energy storage at a much more central role than low-renewable infrastructures. Storage, in the traditional context, is usually referred to as additional capacity to shave peaks, provide reserves, or to have a local backup. Conversely, storage can be a structural enabler in renewable systems with a high sector coupling where not only time, but also carrier and end-use sectors may be traversed by energy. It is significant as a result of its variability in renewable generation, the heterogeneity of demands, and the losses and timing limitations in conversion pathways. In the absence of storage, much of the routing between the sectors would be inoperative although technically feasible, as the system would not have the capacity to absorb temporal imbalances and store the energy value between sectors.

The nature of this structural role is that storage cannot be viewed as a tight category of devices. Storage in multi-form coupling systems is more appropriately thought of as a layer of flexibility within the generation, conversion, network interaction and demand response architecture. Electrical, thermal, chemical, mechanical, and hydrogen-based storage are all forms of storage that have a different balancing role to play, and cannot be evaluated on just intrinsic technical performance but also on the location, and position, of the storage within the system as a whole. A battery in a building microgrid, such as that, is not functionally analogous to hydrogen storage linked to an electrolyzer hub in the region, although both are officially supposed to both absorb renewable excess [56].

The storage comparison should distinguish technology performance from system value. Round-trip efficiency, capital cost, levelised storage cost, lifetime, cycle life, self-discharge, energy density, response time, discharge duration, technology-readiness level, and life-cycle carbon intensity should be reported where comparable data are available. These indicators should not be presented as single universal values because they vary with project scale, operating regime, ambient conditions, depth of discharge, electricity price, equipment configuration, and study year. The revised comparison should therefore report literature-derived ranges, identify the reference year and system boundary, and separate device efficiency from complete pathway efficiency [57].

5.2. Electrical energy storage and fast-response flexibility

The most evident and the most advanced form of renewable integration is electrical energy storage, mostly due to the quick advancement of lithium-ion batteries and related power electronics. Electrical storage is particularly valuable in multi-form coupling systems in terms of short-term balancing, frequency support, ramp smoothing and intra-day energy shifting. It is very reactive, modular and relatively simple to incorporate into distributed systems, which makes it very appropriate for buildings, microgrids, electric vehicle charging systems and local clusters of renewable energy.

Lithium-ion batteries are the most popular due to the high efficiency, quick reaction, and a powerful commercial chain of supply. They frequently play the role of stabilizing the electrical backbone on which other coupling pathways rely. Batteries can minimize curtailment when renewable variations are small, and flexibility requirements are concentrated over short periods, as well as to aid voltage and frequency regulation, and enhance the use of heat pumps or electric charging infrastructure. Electrical storage can be used as the initial defense against variability in this sense.

But the visibility of batteries may result in conceptual overdependence. Battery storage is often considered a general-purpose balancing device in a broad range of planning studies, where the flexibility requirement is far beyond the most economical operating point of battery storage. The trend endangers to simplify the issue of storage in multi-form coupling systems. Although batteries have a high response time to rapid control and cyclic dispatch, they are expensive, non-regenerative, and have a finite lifespan, limiting their utility in long-term renewable scarcity or seasonal load balancing. They are most useful when applied to cope with high frequency variability and maintain electrical stability, rather than when one anticipates them to correct all the system temporal mismatches [58].

This category is extended to other electrical storage technologies. Flow batteries offer more design freedom between power and energy capacity, and can be appealing where storage periods are longer and need not be subject to the cycling constraints of lithium-based systems. Supercapacitors and flywheels are capable of very fast response and high cycling rates, but are limited in their application to a few niche areas of power-quality and transient-support functions by their low energy density. Pumped hydro and compressed air energy storage offer greater-scale electrical balancing, particularly when used at utility or regional scales, but are limited to geographic areas and are more sensitive to infrastructure conditions than modular battery systems. This heterogeneity highlights a significant point of view: electrical storage is essential, yet its internal heterogeneity indicates that no single technology can be used to portray the whole spectrum of electrical flexibility [59].

5.3. Thermal energy storage and the value of low-cost temporal shifting

Thermal energy storage is frequently overlooked in more general discussions of energy transition since it is not as technologically visible as batteries or hydrogen. However, in multi-form coupling systems, it can often be one of the most economical and architecturally pertinent forms of storage. This is especially the case in systems when heating and cooling form a substantial portion of final energy demand. The fact that thermal loads tend to be less intolerant to temporal shifting than electrical loads means that renewable variability can be absorbed at relatively low cost by thermal storage and the electrical system stress is alleviated.

The sensible heat storage, which is usually based on solid media or water tanks, is common due to its simplicity, maturity, and low cost. It is also particularly useful with building-scale and district heating systems where renewable electricity can be used to generate stored thermal energy using heat pumps or electric boilers when the amount of generated energy is excessive. Latent heat storage offers higher energy density and can be useful where space is a consideration or constant temperature ranges are required. Although less commercially developed, thermochemical storage offers higher energy density and longer storage time with lower standing losses, which may be useful for long-duration thermal applications in the future [60,61].

Thermal storage is important in multi-form coupling systems not only for its technical performance but also for its exergy logic. Direct conversion of electricity into all energy services is inefficient when the end product is low-grade heat. Thermal storage can be used to convert renewable electricity into a form that better fits end-use demand, thus maintaining system efficiency not just in the power sector but at the whole-energy level. This has significant design implications. Thermal storage can substitute for some of the balancing load in systems with high heating or cooling loads, which would otherwise be taken up by batteries, thereby costing less to install than batteries and preventing excessive electrification of flexibility provision.

Meanwhile, thermal storage has obvious drawbacks. It is highly dependent on the local demand structure and network situation. It is not as portable as electrical or chemical storage, tends to be more location-specific, and usually cannot store electricity for reintroduction into the system, requiring further conversion processes. Consequently, its flexibility is sector-bound to some extent. However, this does not mean that this has to be perceived as a weakness in absolute terms. The best storage strategy in most coupled systems is one that addresses the flexibility requirements in the sector where they occur, rather than resolving all imbalances by reconverting them to electricity.

5.4. Hydrogen and chemical storage for long-duration and cross-sector flexibility

Hydrogen has acquired special strategic importance among all storage pathways in multi-form coupled systems, as it offers flexibility for renewables beyond the short-term outlook that batteries and many thermal systems can provide. Excess renewable electricity can be converted into hydrogen via electrolysis and stored for use in future power production, industrial processes, transport, or the production of synthetic fuels. This renders hydrogen fundamentally different than short-duration balancing technologies. It is not just a storage unit but a cross-sector energy carrier that can connect the power system to hard-to-electrify sectors.

The architectural appeal of hydrogen is in length, magnitude, and sectoral scope. It can help to balance on a daily, weekly, and, perhaps, seasonal basis, particularly when there are underground or massive storage facilities. It may also decouple renewable production from local electricity demand and open up opportunities to use renewable energy to power industrial heat, chemical feedstocks, shipping, aircraft or long-haul transport. These functions can be very important in systems that are highly decarbonized because direct electrification becomes limited in its practical application [62].

Hydrogen should not be presented as a universally superior storage medium. Its principal advantage is the ability to connect renewable electricity with long-duration storage and hard-to-electrify uses, rather than high round-trip efficiency. The complete electricity–hydrogen–electricity pathway includes electrolysis, gas conditioning, compression or liquefaction, storage, and reconversion, and each stage introduces energy loss, capital cost, maintenance requirements, and operational constraints. Hydrogen systems also require leak detection, ventilation, materials compatible with embrittlement risk, appropriate separation distances, emergency procedures, and standards for production, transport, storage, and end use.

The strongest applications are therefore those in which hydrogen can be consumed directly as an industrial feedstock, high-temperature fuel, transport fuel, or intermediate for synthetic products, or where very long storage duration is required and alternatives are constrained. For short-duration balancing and frequent electricity cycling, batteries or thermal storage are usually more efficient. For low-temperature heating, direct use of electricity through heat pumps is generally preferable to producing hydrogen and then burning or reconverting it. Hydrogen should be selected when its duration, scale, transportability, and sectoral reach compensate for its conversion and infrastructure penalties. This conditional conclusion is more defensible than a general claim that hydrogen is the key storage solution for all highly renewable systems [63].

5.5. Hybrid energy storage systems and coordinated flexibility design

There is no single storage technology that can simultaneously optimize response speed, efficiency, cost, energy capacity, duration, scalability, and cross-sector integration. That is why hybrid energy storage systems have become increasingly topical in multi-form coupling design. A hybrid storage set-up is a combination of technologies that have various strengths such that the whole system can react effectively to various forms of variability. It is not technological redundancy per se, but the complementary functionality [64].

Battery-supercapacitor systems are a canonical example in which supercapacitors handle rapid transients and high-power variations, while batteries handle slower energy balancing. Battery thermal combinations in bigger coupled systems are capable of stabilizing electric demand and out-of-band heating or cooling loads. Battery-hydrogen systems are specifically important as they establish a hierarchy of time: batteries are required to resolve short-term and intra-day balancing, whereas hydrogen is needed to provide long-term and inter-sector flexibility. A combination of thermal and hydrogen could also be used in industrial or district scale systems whereby there are numerous end-use paths, and flexibility needs to be shared both in the temperature and time space.

Task allocation is the most important design knowledge of hybrid systems. Storage technologies are supposed to perform their roles based on their relative advantages and not used as capacity blocks that can be swapped. Once this principle is disregarded, hybridization may turn out to be a costly amassing of assets that cannot use their functions efficiently and have redundant functions. Properly used hybrid storage can also ease the stress on cycling, make systems cost-effective, and make them more resilient through the diversification of balancing paths [65,66].

In this regard, coordinated control is critical. The only instance in which hybrid storage works well is when the dispatch logic is aware of the relative price, degradation curve, speed of response and duration of capability of each component. There is no need to repeatedly cycle a battery to perform low-value long-duration balancing where hydrogen storage can be used to do the same, and there is no need to use hydrogen to do second-level regulation which can be more effectively done by batteries or power electronics. Good hybrid design is thus impossible without functional intelligence and clarity of hierarchy of storage.

5.6. Functional roles of storage across time, scale, and sector

Storage in multi-form coupling systems can only be understood in meaningful terms in the context of its functional roles and not necessarily in its technological types. Storage functions at least at four levels across time. At very short timescales, it corrects power quality, assists frequency control and smoothing of rapid renewable swings. In the short-to-middle term, it coordinates the energy of the day, matches renewable generation with demand peaks, and orchestrates devices that are tied together (like heat pumps and electric vehicles). On longer timescales, it will be a backup in the face of longer renewable shortages and lessening reliance on fossil peaking capacity. At seasonal scales, it can be used to allow renewable energy to be used during high-production seasons to offset low-production seasons or off-power-sector industrial processes [67].

Storage, across scale, also functions differently. It primarily facilitates local balancing, service continuity and self-consumption in buildings and microgrids. It allows electricity, heat, cooling, and process loads to work together in a coordinated manner in district or industrial systems. At the regional or national levels, it is a strategic infrastructure resource that has market design, energy security, and decarbonization implications. These differences are significant since the value proposition of the same technology can vary significantly when it comes to the scale of the system and the context of its coupling.

Storage lies in between the energy quality levels across the sectors. Electrical storage maintains high-grade flexibility, thermal storage smoothes low-grade load, and hydrogen or chemical storage offers renewable energy into industry and mobility options. Their combination is not to delay energy consumption, but to restructure the way renewable energy is allocated between functions, time, and structures [68].

5.7. Critical quantitative comparison

The storage comparison should separate technology performance from system value. Where comparable data are available, round-trip efficiency, capital cost, levelised storage cost, lifetime, cycle life, self-discharge, energy density, response time, discharge duration, technology-readiness level and life-cycle carbon intensity shall be reported. However, these indicators should not be given as a single universal value. They vary depending on the project scale, operating regime, ambient conditions, depth of discharge, electricity price, equipment configuration and the year of the study. Revised tables should therefore include ranges from literature, specify the reference year and system boundary, and distinguish device efficiency from total pathway efficiency.

Electrical storage is generally highly responsive and appropriate to frequent cycling, but economics can degrade when large energy capacity is needed for infrequent or seasonal discharge. Thermal storage usually costs less per unit of thermal energy stored and can be very effective where there is a great thermal demand. The value of thermal storage differs by location and sector. Thermal storage does not usually return electricity without an additional conversion stage. Hydrogen has the advantages of long duration, large-scale storage and direct use in industrial and transport applications. However, the disadvantages of lower electricity-to-electricity efficiency, compression or liquefaction requirements, leakage and embrittlement concerns, infrastructure cost and safety management need to be considered. Chemical carriers could improve transportability or compatibility, but any additional synthesis and reconversion step increases complexity, cost, and energy loss. The only reason for hybrid storage is if the system as a whole results in lower total cost, degradation, curtailment, or reliability risk than a single technology.

Electrical storage is generally very responsive and suitable for frequent cycling, but the economics can be poor where large energy capacity is needed for infrequent or seasonal discharge. Thermal storage usually costs less per unit of thermal energy stored and can be very effective where there is a great thermal demand. The value of thermal storage differs by location and sector. Thermal storage does not usually return electricity without an additional conversion stage. Hydrogen has the advantages of long duration, large-scale storage and direct use in industrial and transport applications. However, the disadvantages of lower electricity-to-electricity efficiency, compression or liquefaction requirements, leakage and embrittlement concerns, infrastructure cost and safety management need to be considered. Chemical carriers can enhance transport or compatibility, but every additional step of synthesis and reconversion adds complexity, cost and energy loss. To justify hybrid storage, the combined system must reduce total cost, degradation, curtailment, or reliability risk more than any single technology. As outlined in **Table 3**, key storage technologies vary significantly in their response time, storage life, functional purpose, scalability, and industry appropriateness, which is why a coordinated implementation is usually better than implementation on a single type of storage [69, 70].

Table 3. Comparative characteristics of major energy storage technologies for multi-form coupling systems.

Storage type	Representative technologies	Typical storage duration	Response speed	Main role in coupled systems	Main strengths	Main weaknesses	Most suitable scale/applications
Electrical storage	Lithium-ion batteries	Seconds to several hours	Very fast	Fast balancing, peak shaving, renewable smoothing, local backup	High efficiency, mature technology, modularity	Cost for long-duration use, degradation under frequent cycling	Buildings, microgrids, EV charging systems
Electrical storage	Flow batteries	Hours to tens of hours	Fast	Medium-duration balancing and renewable shifting	Flexible scaling of energy and power, long cycle life	Lower energy density and higher complexity than lithium-ion	Microgrids, commercial and industrial systems
Electrical storage	Supercapacitors	Seconds to minutes	Extremely fast	Power quality support and transient stabilization	Very high power density and cycle life	Very limited energy capacity	Power electronics support, fast transient applications

Table 3. *Cont.*

Storage type	Representative technologies	Typical storage duration	Response speed	Main role in coupled systems	Main strengths	Main weaknesses	Most suitable scale/applications
Electrical / mechanical storage	Flywheels	Seconds to minutes	Extremely fast	Frequency support and short-term stabilization	High cycle life and fast response	Limited duration and self-discharge	Grid-support and industrial quality applications
Mechanical storage	Pumped hydro storage	Hours to days	Medium	Bulk electricity storage and grid balancing	Large-scale capacity, mature technology, long lifetime	Geographic dependence and high infrastructure requirements	Utility-scale and regional systems
Mechanical storage	Compressed air energy storage	Hours to days	Medium	Large-scale balancing and reserve provision	Large capacity potential and long duration	Lower efficiency, location constraints, system complexity	Regional and utility-scale applications
Thermal storage	Sensible heat storage	Hours to days, sometimes seasonal	Medium	Heat load shifting and renewable electricity absorption through power-to-heat	Low cost, mature, efficient for thermal applications	Sector-bound flexibility and limited portability	Buildings, district heating, industrial heat systems
Thermal storage	Latent heat storage	Hours to days	Medium	Compact thermal buffering in controlled temperature ranges	Higher energy density than sensible storage	Material cost and design complexity	Building systems, cooling and heating applications
Thermal storage	Thermochemical storage	Days to seasonal	Slow to medium	Long-duration and potentially seasonal heat storage	High theoretical energy density and low standing losses	Lower maturity and practical complexity	Seasonal thermal systems, future large-scale heat storage
Hydrogen storage	Compressed/liquefied/ underground hydrogen	Days to seasonal	Slow to medium	Long-duration balancing and cross-sector energy transfer	Strong sectoral reach and seasonal capability	Low round-trip efficiency and infrastructure intensity	Industrial hubs, regional systems, strategic storage
Chemical storage	Ammonia, methanol, synthetic methane, Liquid organic hydrogen carrier (LOHC)	Weeks to seasonal	Slow	Energy transport, long-duration storage, fuel substitution	Easier transport or compatibility with existing infrastructure	Additional conversion losses and process complexity	Industry, shipping, regional and export-oriented systems
Hybrid storage	Battery + thermal/battery + hydrogen/battery + supercapacitor	Multi-timescale	Multi-speed	Coordinated short-, medium-, and long-duration flexibility	Functional complementarity and better system optimization	Higher control complexity and coordination requirements	Coupled microgrids, industrial parks, regional energy hubs

5.8. Technology maturity and deployment relevance

Technology maturity should be separated from theoretical potential. Mature and widely deployed options, including lithium-ion batteries, sensible-heat storage, heat pumps, pumped hydropower, conventional district-heating storage, and established combined heat and power technologies, have relatively well-characterised performance and supply chains. Early-commercial or demonstration-stage solutions, including some flow-battery chemistries, large hydrogen hubs, advanced compressed-air systems, thermochemical storage, liquid organic hydrogen carriers, and integrated synthetic-fuel pathways, may offer valuable functions but have less certain cost, durability, and operational evidence. Emerging concepts should be evaluated using technology-readiness level, demonstration scale, cumulative operating hours, availability of standards, supply-chain maturity, and bankability. Combining mature and emerging technologies in one undifferentiated comparison can exaggerate the near-term relevance of concepts that remain dependent on research, policy support, or specialised infrastructure [71].

6. Comparative assessment, modeling, and optimization methods

6.1. Why comparative assessment is essential in multi-form coupling systems

Comparative assessment is an action step measure in the study of renewable energy systems of multi-form coupling, as such systems comprise multi-technology, multi-carrier of energy and multi-decision levels. Unlike more traditional single-energy systems, where component analysis can be conducted in a fairly limited technological context, multi-form coupling systems demand the concomitant evaluation of flexibility, conversion efficiency, storage life, compatibility with infrastructure, cost, carbon performance, and reliability. A technology that seems very attractive when considered on its own can result in restricted value when integrated into a coupled architecture, whereas a less efficient technology can become strategically significant as it can allow long-duration balancing or cross-sector decarbonization [72].

This renders comparative evaluation beyond a ranking undertaking. It is actually meant to show the circumstances in which a technology, pathway or design strategy generates system value. As an example, in short-duration balancing, batteries could be more effective than hydrogen storage due to greater round-trip efficiency and responsiveness, whereas hydrogen could be more useful in systems with a high seasonal imbalance or industrial load. Equally, thermal storage can demonstrate reduced formal versatility than electrical storage, however, where heating-based systems are involved, it can provide more economic advantage since it can provide the greater flexibility requirement at a reduced cost. Comparative evaluation is thus situational and it cannot be narrowed down to the quest for globally better technologies.

The main problem of the literature is that most comparative studies are device-focused and do not take into account interactions at the whole-system level. The comparison of various technologies is frequently made with the help of isolated performance measures, e.g., efficiency, energy density or unit cost without having enough consideration of coupling functionality, network integration, or operational role. This may result in inaccurate inferences especially in systems where both storage and conversion devices would be of value based on complementary performance as opposed to independent performance. A stricter comparative framework should then be able to bridge the gap between component measurements and system-wide goals and architectural functionality [72].

6.2. Techno-economic and environmental comparison of storage and coupling options

Multi-form coupling studies most often depend on techno-economic analysis as the most common basis of comparison. Commonly used metrics in assessing storage technologies, conversion pathways and integrated system designs are metrics like capital expenditure, operating cost, levelized cost of storage, payback period, and total system cost. The metrics are essential since economic viability greatly influences the ability of any technology to be transferred to the actual implementation phase, after its modeling stage. There are however, interpretations of cost comparisons in coupled systems. The perceived cost of a storage or conversion technology can tend to vary with the extent to which the system benefits are reflected in its cost. A battery that is only checked based on a direct arbitrage revenue can seem uneconomic, whereas the same battery can be very valuable when it includes grid support, peak reduction, renewable curtailment avoidance, and reliability services [73].

This is equally true of cross-sector technologies, like electrolysis, district heating storage, or power-to-fuel pathways. They do not often have any single market signal that can define their economics, since they are value creators across infrastructures and timescales. Consequently, such targeted techno-economic comparisons can underestimate technologies whose utility cuts across industries, as opposed to being concentrated in a single measure of operation. One of the reasons why integrated cost assessment is more applicable than component-level cost comparison in multi-form systems is because of this. Not only what a technology costs, but also what it replaces are the costs of systems, and what is possible with flexibility.

Comparison between the environment is also necessary and particularly so since the goal of multi-form coupling is directly related to deep decarbonization. The long-term desirability of storage and conversion pathways is influenced by carbon emissions, life-cycle, resource consumption, recyclability, and the criticality of materials. Environmental assessment, however, must be critically interpreted. Low operational emission technologies might have large upstream impacts in terms of material extraction, manufacturing energy requirement or infrastructure construction. On the other hand, technology with an intermediate level of conversion losses could still facilitate better carbon performance when it makes it possible to utilize high levels of renewables and replace fossil consumption in those sectors that are the hardest to decarbonize [73].

This implies that environmental comparison has to go beyond direct efficiency. An efficient system is good, but not the only factor of sustainability in coupled systems. The effect of a low-efficiency route to more extensive fossil substitution can be more climate-efficient than that of a high-efficiency route to a single sector. Thus, the techno-economic and environmental aspects must be compared rather than viewed independently. The best technologies to be considered for greatest policy relevance do not necessarily have the highest performance individually, but rather the highest overall benefits in cost reduction, carbon reduction, and system flexibility [24,38].

6.3. Performance metrics and the problem of metric selection

The selection of performance measures plays a major role in making inferences in comparative studies. Round-trip efficiency, response speed, power density, energy density, cycling capability, lifetime, depth of discharge, and operational reliability are common technical indicators. These metrics are handy, but they cannot be used in a multi-form coupling system as their meaning is system-dependent. For example, round-trip efficiency is key to short-cycle storage but less important to seasonal storage, where time and infrastructure scale are more critical to system value. Similarly, high power density is important for rapid power balancing, but not for thermal storage, where energy volume and cost per unit heat of storage are more critical.

The danger is that the wrong choice of metrics might give a biased technology evaluation to dimensions that are familiar or are easy to measure. Batteries will perform well on efficiency and response and hydrogen will perform well on duration and sectoral versatility. In heating-intensive applications, thermal storage may seem less impressive compared to power-system-oriented scales, even though it can be the most viable solution. This implies that metrics ought to be selected based on the service being evaluated, rather than using an off-the-shelf template [74].

The other problem is that most studies focus on component measures and do not adequately capture system-level measures such as renewable utilization rate, adequacy of flexibility, contribution to resilience, reduction in curtailment, or the ability to delay infrastructure growth. These are broader indicators that are more difficult to quantify but may be more applicable to real planning decisions. Multi-form coupling systems have performance which is emergent and not necessarily additive. A storage technology is not just a technical output; it alters the behaviour of the whole coupled architecture. For that reason, a strong comparative framework would be able to integrate component measures with system-level measures and clearly identify the trade-offs between them [75].

6.4. Modeling approaches for coupled renewable energy systems

The analytical interface between system architecture and the actual decision-making is modelling. Since multi-form coupling systems have many carriers, conversion links, networks, and timescales, the modelling techniques must trade off physical realism with computational tractability. At the simplest, models are steady-state or dynamic, deterministic or stochastic, centralized or distributed, and component-based or system-integrated. Every modelling decision reflects a presumption about which aspects of the coupled system are most important.

Linear models, steady-state models, and simplified linear models are very popular in planning studies, as they enable the optimization of large systems at a manageable computational cost. They can be applied to capacity sizing, comparative investment analysis, and long-term structural analysis. But these models may miss time dynamics, start-up limitations, thermal inertia, and control-response limitations, which are salient in actual operation. Dynamic models, in contrast, capture transient behaviour, network behaviour and device level response more effectively, but need more assumptions, more data, and computational resources. Consequently, the decision between model simplicity and realism is not a technical one per se; it defines what types of conclusions about design can be made [24].

One common shortcoming in the literature is the distinction between operational and planning models. Simplified dispatch behavior is often used in investment studies, and fixed system configurations are used in operational studies. When coupled with renewable systems, this separation is problematic since the operation and design are highly interdependent. A storage technology that appears favorable in a perfect world of dispatch might behave differently with the addition of network congestion, forecast uncertainty, or control constraints. Similarly, the configuration of generation, storage and conversion capacities is very critical to operational strategies. This indicates that there is a necessity to have more unified modeling frameworks that will tie long-term planning and short-term operation together.

The other modeling issue of concern is the multi-time scale interaction. Transport loads, electricity, thermal networks, and hydrogen systems evolve across various temporal rhythms. All of these are hard to capture in a single model, and ignoring these differences can bias the valuation of flexibility. A good modeling practice thus would need the use of temporal layering or decomposing the system to be represented at various levels of resolution based on the dynamics of the various subsystems. This is particularly relevant in considering hybrid storage or sector-coupling paths whose value is directly determined by timescale complementarity [76].

6.5. Optimization methods and their strengths and limitations

The design and functioning of multi-form coupling systems rely on optimization since it offers a formal method of coordination of conflicting goals and restraints. Mixed-integer and linear programming have been extensively used in planning and scheduling as they provide an optimal trade-off between detail in the model and solvability. They work well, especially when relationships within a system can be well approximated as a linear relationship, when discrete decisions have to be modeled (unit commitment, choice of technology or expansion of a network).

The nonlinear programming is required in cases where efficiencies, thermodynamic relationships, or network flows could not be properly linearized. It is able to enhance realism but tends to do so at the expense of computational complexity and diminished global optimality assurances. Stochastic optimization can be applied to model uncertainty in renewable generation, demand and prices and robust optimization is concerned with performance under bad conditions without making probabilistic assumptions. Both play significant roles in renewable dominated systems yet they also represent various design philosophies. Stochastic approaches are aimed at the expected optimality in case of modeled uncertainty, and robust approaches are aimed at the resilience in case of worst-case deviations. The right decision is based on the importance to the system operators of economic efficiency or operational security [77].

Multi-objective optimization is particularly applicable to coupled systems since cost, emissions, flexibility and reliability are seldom optimized. However, multi-objective approaches also pose interpretation issues. The presence of a Pareto frontier is not a solution to design choice by itself, but rather it makes trade-offs clear. Even the final decisions remain as policy priorities, stakeholder preferences and practical deployment constraints. This brings out a bigger argument; optimization is a decision-support, and not a substitute for judgment.

Genetic algorithms and other heuristic and metaheuristic algorithms such as particle swarm optimization are commonly applied in search spaces that are very nonlinear or discrete in nature. They are flexible and powerful, especially in terms of size of hybrid storage, or complicated scheduling issues, but they can have limitations in terms of reproducibility and scalability. Tuning of parameters can also be critical to their results. When analyzing using SCI-standard methods, one should not, therefore, approach these techniques critically or equate the level of computational sophistication with a superior methodology [78].

6.6. Data-driven and AI-enhanced methods

With the further digitalization of renewable energy systems, the use of data-driven approaches to forecasting, control, and optimization is becoming more prominent.

Machine learning has become common in the prediction of renewable generation, prediction of load, fault diagnosis of equipment, and modelling user behaviour. These predictive benefits can be very beneficial in the context of multi-form coupling systems where timing accuracy in the scheduling is greatly improved as well as lessening the necessity of conservative reserve margins. Real-time dispatch and self-learning energy management has also been of interest to reinforcement learning and the adaptive control methods [79].

Their advantage is that they can be used to deal with nonlinear relationships, high-dimensional data, and evolving system states. This is, however, subject to their practical value based on the quality of the data, the interpretability and strength. Most AI-based work demonstrates good performance in simulation, but is poorly supported by real operational limitations. Black-box models can also decrease transparency, which is not good in infrastructure planning and critical energy operations where explainability and trust are crucial.

Data-driven methods can best play a complementary role; they cannot replace. They are best applied in the context of physically informed structures that maintain engineering logic and enhance prediction and flexibility. Coupled energy systems, systems where thermodynamics, infrastructure constraints, and safety requirements are determinant, hybrid modeling strategies that integrate data-driven learning with physics-based optimization will tend to be more plausible than black-box strategies [80].

6.7. Simulation tools, validation, and future methodological needs

Multi-form coupling studies have been conducted on a variety of simulation platforms, such as MATLAB/Simulink, TRNSYS, HOMER, EnergyPLAN, and Modelica-based platforms. They both have their benefits with regard to the research question. Others are more appropriate when it comes to the detailed component dynamics, whereas others are more robust with respect to long term planning or scenario analysis. Each platform cannot be used in all situations, and the tool used may tend to affect the degree of abstraction as well as the nature of conclusions drawn.

One of the long-standing methodological gaps is validation. Most analyses are based on very idealized case studies, presumed demand models, or artificial weather data, and are not often calibrated on real-world operating experience. This leads to a lack of confidence in comparative assertions, when the relative value of storage and coupling pathways can change with small modeling assumptions. To move multi-form coupled systems beyond having theoretical potential to engineering utility, more empirical support is required, in the form of demonstration projects, measured data, and cross-model comparison [81].

6.8. Practical distinction among modelling approaches

Model selection should follow the decision problem. Steady-state and linear optimisation models are most appropriate for long-term capacity planning, technology screening, and scenario comparison when temporal and network dynamics can be simplified. Their computational efficiency permits large spatial and temporal domains, but they may overlook ramping, thermal inertia, degradation, start-up constraints, and transient limits. Dynamic models are more suitable for controller design, stability analysis, thermal-network behaviour, device interaction, and short-timescale validation, although they require more detailed parameters and impose greater computational burden.

Deterministic models are useful when forecasts and operating conditions are sufficiently stable or when a transparent baseline is required. Stochastic optimisation is preferable when probability distributions for renewable generation, demand, prices, or failures can be estimated and when expected performance across scenarios is relevant. Robust optimisation is more appropriate when uncertainty bounds are available but probability distributions are unreliable, particularly for conservative planning and security-constrained scheduling. Distributionally robust methods occupy an intermediate position by protecting decisions against ambiguity in the assumed probability distribution [82].

Multi-objective optimisation should be used when cost, emissions, reliability, resilience, and renewable utilisation cannot be represented credibly by a single weighted objective. The resulting Pareto frontier allows decision-makers to observe the cost of improving one objective relative to another. Model predictive control is suitable for real-time or receding-horizon operation because it repeatedly updates schedules using new forecasts and system states. Agent-based and distributed optimisation methods are relevant where assets have different owners, local autonomy is important, or centralised data exchange is restricted. Artificial-intelligence methods can support forecasting, surrogate modelling, anomaly detection, and adaptive control, but they should not replace physical constraints or engineering verification.

In the future, integration is the key methodological requirement. Comparative analysis, system modeling, optimization and control analysis are far too often performed in parallel, but not in a coherent system. The research in the future needs to shift to integrated approaches to relate life-cycle and techno-economic comparison to dynamic operation, uncertainty treatment, and multi-scale planning. This integration is critical in case modeling and optimization can be used to not only facilitate academic knowledge but will also provide plausible deployment decisions in renewable energy systems in terms of multi-form coupling. **Table 4** compares the key assessment, modeling, and optimization techniques in the literature, their strengths, limitations, and applicability in various decision contexts in coupled renewable systems [83].

Table 4. Comparative overview of assessment, modeling, and optimization methods for multi-form coupling systems.

Method category	Typical methods/tools	Main purpose	Strengths	Limitations	Most suitable use cases
Techno-economic assessment	CAPEX/OPEX analysis, levelized cost metrics, payback period, net present value	Evaluate economic feasibility of storage, conversion, and integrated system designs	Direct decision relevance and strong comparability	May undervalue cross-sector and non-market benefits if narrowly defined	Technology screening, early-stage feasibility, policy comparison
Environmental assessment	Life-cycle assessment, carbon footprint analysis, material/resource analysis	Evaluate environmental sustainability and emission reduction potential	Captures impacts beyond operational efficiency	Sensitive to boundary assumptions and data quality	Sustainability comparison, policy support, technology roadmapping
Deterministic system modeling	Linear and simplified steady-state models	Capacity planning, basic dispatch, system configuration analysis	Computationally tractable and suitable for large scenario sets	Limited treatment of uncertainty and dynamic behavior	Long-term planning and broad scenario analysis

Table 4. *Cont.*

Method category	Typical methods/tools	Main purpose	Strengths	Limitations	Most suitable use cases
Dynamic simulation	Time-series simulation, component dynamic models, network simulation	Analyze transient behavior, operational interactions, and control response	Better physical realism and operational insight	More data-intensive and computationally demanding	Detailed operation, control testing, device interaction analysis
Optimization methods	LP, MILP, NLP, stochastic optimization, robust optimization, multi-objective optimization	Determine optimal planning and dispatch decisions under constraints	Strong formal decision support and trade-off analysis	Results depend on assumptions, objective formulation, and model simplification	Sizing, scheduling, uncertainty management, Pareto analysis
Heuristic/metaheuristic methods	Genetic algorithm, particle swarm optimization, ant colony optimization	Solve highly nonlinear or combinatorial design problems	Flexible and adaptable to complex search spaces	May lack reproducibility, global optimality guarantees, and scalability	Hybrid storage sizing, complex topology optimization
AI/data-driven methods	Machine learning forecasting, reinforcement learning, predictive control	Improve forecasts, adaptive scheduling, and intelligent management	Handles nonlinearities and large datasets well	Data dependence, limited interpretability, uncertain real-world robustness	Forecasting, adaptive control, digital energy management
Simulation platforms	MATLAB/Simulink, HOMER, TRNSYS, EnergyPLAN, Modelica	Support scenario analysis, component simulation, and integrated system studies	Widely used and suitable for different abstraction levels	Platform choice can bias model structure and conclusions	Case study simulation, cross-validation, tool-assisted design
Integrated assessment frameworks	Techno-economic-environmental-operational coupled frameworks	Jointly assess cost, carbon, reliability, and flexibility	Better reflects whole-system value	Methodologically demanding and often data-heavy	SCI review synthesis, decision support for deployment pathways

Note: CAPEX: capital expenditure; OPEX: operating expenditure; LP: linear programming; MILP: mixed-integer linear programming; NLP: nonlinear programming; AI: artificial intelligence; SCI: science citation index.

7. Challenges, research gaps, and future development trends

7.1. Technical challenges in highly coupled renewable energy systems

Even though multi-form coupling is an interesting avenue to enhance the use of renewable energy and decarbonize energy further, its practical use is not that simple. The main difficulty is that the process of increasing flexibility and at the same time the complexity increase occur simultaneously because of the coupling. The connection of electricity, heat, cooling, hydrogen, gas and transport provides the system with a greater balancing choice but also makes it more vulnerable to the quality of coordination, compatibility and dynamism between sectors. That is, the technical benefit of coupling cannot be separated out of the technical cost of the overhead of interdependence [84].

Among the major difficulties is the multi-timescale of system functioning. Power has to be matched almost immediately, thermal systems change more slowly due to inertia and storage responses and hydrogen or chemical processes tend to be matched over much longer timescales. The differences are not just the operational specifics; these differences are the pillars on which the flexibility might be taken out of the system. Unless the control and scheduling strategies are correctly balanced with these temporal properties, the system can run inefficiently dispatched, over-cycled assets, or underutilized slower yet more cost-effective flexibility resources. This particularly presents an issue in the co-location of fast-response batteries, thermal buffers, demand response, and long-duration hydrogen storage in architectures, as the optimal operating envelope of each resource differs.

A second technical issue is related to the propagation of uncertainty. The generation of renewable energy is subject to weather changes, the demand is sensitive to weather, and transport and building activities become more dynamic as users. In a coupled system uncertainty is not isolated in one energy carrier. A prediction error in solar energy, such as one, can impact electricity dispatch, heat pumps, hydrogen production, and charging at the same time. This coupled uncertainty has the potential to increase control challenges and reveal vulnerability in deterministic planning assumptions. The larger, the tighter-coupled the system is, the greater the importance of the realization of how uncertainty flows through interfaces as opposed to the movement of uncertainty through isolated subsystems.

The other issue is the interoperability of infrastructure. Multi-form coupling demands that devices, networks and digital platforms share information and react in a coherent manner in response to shared goals. However, the infrastructures in question were usually created in the past with different purposes and in different technical specifications and institutional frameworks. Power grids, district heating systems, gas pipelines, hydrogen facilities, building management systems, and mobility platforms are not inherently coordinated. This poses integration challenges both physically and information wise. Weak interoperability can undermine the theoretical flexibility of coupling with disjointed control, lack of consistency of data quality, and incompatible operational constraints [85].

Another technical problem is the stability of the system and cascades. Coupling enables another subsystem to be supported by another but it also provides avenues through which disturbances can propagate. In an electrified heating system (highly), a power deficit can readily affect thermal comfort. With hydrogen-integrated architectures, the failure of an electrolyzer cluster or compressor can have an impact on storage strategy as well as the industrial supply. These dangers imply that steady-state efficiency alone cannot be used to determine technical success of coupled systems. The ability to stay stable when disturbed, graceful degradation when in failure and the ability to isolate or contain faults are also important design requirements.

7.2. Economic, market, and policy barriers

There are significant barriers, both economic and institutional, to the step between technical viability and actual implementation. Multi-form coupling systems are capital intensive in that they can frequently necessitate concomitant investment in renewable generation and storage, conversion technologies, control platforms and network upgrades. Although the benefits of long-term systems may be substantial, the initial cost of the system may be slow to be adopted, particularly in areas where there is still a conservative approach to infrastructure funding, or where policy backing is fragile. This is among the reasons why a lot of good multi-energy concepts continue to exist at pilot projects, industry demonstrations or highly subsidized settings.

One of the major economic issues is that the value generated through coupling is usually shared among a variety of sectors whereas the task of investment is dispersed. The use of a thermal storage system can lower the peak electricity charges, enhance the use of renewable resources, and delay network upgrades, but the benefits could go to other parties. Likewise, curtailed renewable electricity can be converted into hydrogen, which can provide value to balancing power systems, decarbonize industries, and replace transport fuels, but no single market approach can pay off all of these services. This disintegration undermines incentives to invest in coordination and may result in economically rational technologies being unappealing in the eyes of individual actors [86].

The existing market forms are also inclined to abide by traditional sectoral boundaries. The electricity markets tend to be more developed than the heat, hydrogen, or flexibility markets and the pricing mechanisms do not always represent the entire value of cross-sector balancing. Consequently, in academic models coupled systems can be optimized, but in practice, they are commercially underdeveloped due to the narrowness of real market signals, their short-term nature, or their intermittent nature in support of investment. This is particularly problematic in the absence of established remuneration schemes to cover longer storage periods, prevent curtailment, resilience services or carbon-compensated flexibility [87].

The uncertainty of policy also makes deployment more difficult. Multi-form coupling is strongly reliant on the long-term expectations concerning the carbon pricing, renewable incentives, hydrogen strategies, and the efficiency regulations as well as infrastructure planning. When the policy frameworks change often or are sector specific the developers run a high risk of stranded assets or misalignment of investment. This is especially applicable to hydrogen and synthetic fuel routes, the viability of which is highly sensitive to future regulation and formation of industrial demand. Thus, the innovation of coupled renewable systems is not simply a technical shift but a governance issue that will also demand coordinated sector-wide policies that will be traditionally regulated separately [66].

7.3. Safety, standardization, and governance issues

With an increase in the level of coupling, the concerns of safety and standardization take center-stage in the development of the system. This is particularly the case of storage technologies and conversion pathways that contain hydrogen and high capacity batteries, pressurized gases and thermally integrated infrastructure. Safety cannot be considered as a secondary compliance concern that is added to the system design at the end; it has to be part and parcel of the architecture as the ramifications of failure may spread out to related subsystems.

This is depicted by hydrogen. It has a significant strategic worth as a long-duration and cross sector energy carrier; however, its storage, compression, transport, and end use have raised concerns regarding leakage, flammability, embrittlement, and design of the facility. Massive battery systems also pose thermal runaway and fire hazards which are aggravated by the fact that they are more severe when installations are clustered or not closely supervised. Thermal storage and even district-scale infrastructure containment, pressure and operational reliability issues apply. With multi-form coupled systems, the problem is not just that each technology has its safety requirements but that interactions between technologies can result in compound risks [88].

In most aspects, standardization is still wanting. The data protocols, communication interfaces, operational definitions of flexibility, safety certification pathways and integrated planning methodologies remain fragmented sectors and jurisdictions. This slows deployment as developers have to deal with unknown technical needs and interoperability cannot be guaranteed between assets of different vendors or domains of infrastructure. Replicability is also restricted by a lack of standardization. Demonstration projects can operate under very bespoke circumstances, but such an experience is hard to scale unless there are common standards of integration and performance assessment [89].

Another layer of difficulty is that of governance. The multi-form coupling systems have a tendency to cross the administrative, regulatory, and ownership territory. One of these systems can include utilities, industrial operators, building owners, mobility providers, technology vendors, and local authorities. The eventual lack of clear structures of governance makes decision making slow and responsibility diffuse. The latter is of particular concern to infrastructure investment and risk management, where long-term planning involves institutional coordination, which is lacking in disaggregated energy transitions [90].

7.4. AI risks and governance

The application of artificial intelligence introduces risks that must be treated as design constraints. Data-driven models are sensitive to missing data, measurement error, non-representative training sets, changing user behaviour, equipment ageing, and distribution shift caused by extreme weather or market changes. A controller that performs well in historical data may produce unsafe or economically undesirable decisions when operating conditions move beyond the training domain. Black-box models also make it difficult to explain why a dispatch action was selected, which can impede operator trust, regulatory approval, fault diagnosis, and accountability.

AI-enabled control should therefore be embedded within a layered safety architecture. Physical operating limits, network constraints, reserve requirements, and emergency rules should remain explicit and enforceable. Physics-informed learning, constrained reinforcement learning, uncertainty quantification, interpretable surrogate models, and human-supervised operation can reduce but not eliminate risk. Cybersecurity must cover sensor authentication, communication integrity, access control, model tampering, false-data injection, and secure software updates. Before field deployment, algorithms should be tested through out-of-sample validation, stress scenarios, hardware-in-the-loop experiments, failure-mode analysis, and staged demonstration. A fail-safe mode should maintain essential services when communication, forecasts, optimisation, or AI components fail.

7.5. Strengths and limitations

The principal strength of this review is its integration of system architecture, coupling pathways, storage functions, comparative indicators, and modelling methods within a single decision-oriented framework. The analysis covers multiple energy carriers, system scales, storage durations, and application sectors, which allows technology performance to be interpreted in relation to the service required. The explicit distinction between component metrics and whole-system value also reduces the risk of ranking technologies using a single indicator such as efficiency or capital cost.

The review nevertheless has limitations. Published studies use heterogeneous system boundaries, reference years, cost assumptions, climate conditions, demand profiles, and definitions of efficiency, which restrict direct numerical comparison. Evidence from laboratory studies, optimisation models, pilot projects, and commercial installations cannot always be combined without qualification. The availability of field data is uneven, particularly for long-duration hydrogen, thermochemical storage, and complex Power-to-X systems. The review may also be affected by publication bias, database coverage, language restrictions, and incomplete reporting in the primary literature. Quantitative ranges should therefore be interpreted as context-dependent evidence rather than universal design values, and the proposed framework should be validated through common benchmark cases and measured demonstration projects [91].

7.6. Research gaps and future trends

The identified challenges define a direct research agenda. Inconsistent system boundaries require harmonised reporting protocols and open datasets. Weak comparison across coupling pathways requires common benchmark systems and service-based performance indicators. Limited long-duration evidence requires measured demonstrations with transparent operational data. Fragmented planning and control studies require integrated models that connect investment decisions with degradation, uncertainty, network limits, and real-time operation. Cybersecurity and black-box risk require explainable, physics-constrained, and fail-safe artificial-intelligence architectures. Institutional fragmentation requires market and governance arrangements that allocate costs and benefits across electricity, heat, gas, hydrogen, transport, and industrial stakeholders. Future work should therefore link each proposed technical development to a clearly defined evidence gap and should report validation conditions sufficiently well to support comparison and replication [92,93].

Resilience analysis is another area that is not well developed. Most studies maximize cost and emissions in the usual state of operation and little attention is given to extreme events, infrastructure failure, cyber-physical risks and supply disruption. This exclusion is important since the future low-carbon systems will be subject to climate-related strains, as well as increasing digital reliance. A system which works well under average conditions might not be sufficient in cases of disruption where the system is not capable of supporting necessary services [94].

Lastly, most studies are regionally or technologically limited. Findings made in a single climate, policy regime, or infrastructure setting are quickly generalised. Local resource profiles, urban form, industrial structure and legacy infrastructure will be vital in determining the future of multi-form coupling. A larger number of comparative studies across settings are thus required, especially those studies that focus on how the principles of design should vary between building scale, industrial, regional and national application.

The convergence of further electrification, selective molecular energy pathways, digital intelligence, and even more integrative carbon governance is likely to influence the future development of renewable energy systems in the context of multi-form coupling. An evident trend is the ever-increasing sector coupling as energy systems transition to decarbonization of entire systems beyond isolated deployment of renewables. Electricity will continue to be the prevailing backbone though this is not likely to be the only carrier. In its place, more frequent use will be made of thermal networks, hydrogen systems and flexible demand to take in renewable variability and find applications where direct electrification is not as viable [95–97].

8. Conclusion

This review shows that renewable multi-form coupling should be designed as a coordinated system of energy sources, conversion routes, storage assets, networks, control, and end-use services. The value of coupling does not increase automatically with the number of technologies. It increases when each pathway performs a clearly defined function and when conversion losses, storage duration, infrastructure, cost, carbon reduction, and operational risk are assessed at the whole-system level.

Direct electrification remains the preferred route where electrical end use is feasible and network constraints are manageable. Electricity–heat and electricity–cooling coupling can provide particularly effective flexibility when thermal demand is large because heat pumps, thermal networks, and thermal storage avoid unnecessary reconversion to electricity. Batteries and other fast electrical storage technologies are most appropriate for high-power response, renewable smoothing, local reliability, and intraday energy shifting. Their use becomes less attractive when very large energy capacity is required for infrequent discharge.

Hydrogen and chemical carriers have a different and more conditional role. They can extend renewable energy across weeks, seasons, regions, and hard-to-electrify sectors, but this value must be balanced against complete-pathway losses, infrastructure investment, safety requirements, and operational complexity. Hydrogen is therefore best understood as a strategic complement to direct electrification, batteries, and thermal storage rather than as a universal replacement. Hybrid storage can improve performance when each technology is assigned to the timescale and service for which it has a comparative advantage.

The review also demonstrates that technology selection and model selection must be linked. Steady-state optimisation is suitable for strategic planning and capacity screening; dynamic models are required for transient and control questions; stochastic and robust methods are needed when uncertainty materially affects decisions; and multi-objective approaches are necessary when economic, environmental, reliability, and resilience objectives conflict. Artificial intelligence can improve forecasting and adaptive management, but it should operate within physical constraints and be supported by explainability, cybersecurity, fail-safe control, and field validation.

The scientific contribution of this study is the transformation of fragmented literature into a common decision framework that relates local conditions and service requirements to coupling pathways, storage duration, maturity, and modelling method. This framework advances existing reviews by explaining not only what technologies are available, but why, when, and under which constraints they should be selected. It also clarifies that efficiency, cost, carbon mitigation, infrastructure compatibility, flexibility, safety, maturity, reliability, and resilience must be considered together.

For practice, planners should first define the required energy service and flexibility timescale, then screen technically feasible pathways using common criteria before conducting detailed optimisation. Policymakers should support interoperable standards, transparent carbon accounting, multi-sector market participation, and demonstration projects that report comparable performance data. Future research should develop open benchmark systems, harmonised technology and cost datasets, integrated planning–operation–control models, quantitative resilience assessment, life-cycle analysis with consistent boundaries, and long-term field validation of hydrogen, thermochemical, hybrid storage, and AI-enabled control. These developments are necessary to convert multi-form coupling from a broad conceptual vision into reproducible, scalable, and economically defensible energy-system design.

Funding: This work received no external funding.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Data availability statement: All data is presented in the article.

Conflict of interest: The author declares no conflict of interest.

AI use statement: The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

1. Taghavi M, Lee CJ. Development of a novel hydrogen liquefaction structure based on liquefied natural gas regasification operations and solid oxide fuel cell: Exergy and economic analyses. Fuel. 2025; 384: 133826.
2. Taghavi M, Yoon HJ, Chol JU, et al. Innovative Structure of a Liquefied Natural Gas (LNG) Process by Mixed Fluid Cascade Using Solar Renewable Energy, Photovoltaic Panels (PV), and Absorption Refrigeration System. In: Manenti F, Reklaitis GV (editors). Computer Aided Chemical Engineering: 34th European Symposium on Computer Aided Process Engineering/15th International Symposium on Process Systems Engineering, Proceedings of the 34th European Symposium on Computer Aided Process Engineering (ESCAPE34) combined with the 15th International Symposium on Process Systems Engineering (PSE24); 2–6 June 2024; Florence, Italy. Elsevier; 2024. 53, pp. 2071–2076.
3. Dincer I, Aydin MI. New paradigms in sustainable energy systems with hydrogen. Energy Conversion and Management. 2023; 283: 116950.
4. Haldar A, Sethi N. The Twin Challenges—Understanding Energy Poverty and Climate Change. In: Reconciling Energy Poverty and Climate Change: Universal Energy Access and Net-Zero Emission. Springer; 2025. pp. 1–53.
5. Liu M, Zhang B, Wang J, et al. Optimal configuration of wind-PV and energy storage in large clean energy bases. Sustainability. 2023; 15(17): 12895.
6. Gan KE, Taikan O, Gan TY, et al. Enhancing renewable energy systems, contributing to Sustainable Development Goals of United Nation and building resilience against climate change impacts. Energy Technology. 2023; 11(11): 2300275.
7. Li J, Xu W, Yang J, et al. Key technological challenges and systemic solutions for lunar base energy systems designed for long-term deployment needs. npj Space Exploration. 2026; 2(1): 12.
8. Mei S, Wang J, Tian F, et al. Design and engineering implementation of non-supplementary fired compressed air energy storage system: TICC-500. Science China Technological Sciences. 2015; 58(4): 600–611.
9. Ajewole T, Olabode O, Ariyo F, et al. Conceptual perspective of renewable energy resources: A paradigm shift in combating world climate change. In: Vaish A, Kumar Goswami P, Bhatia S, et al. (editors). Adaptive Power Quality for Power Management Units Using Smart Technologies. CRC Press; 2023. pp. 67–103.
10. Xiao B, Gao Z, Peng H, et al. Robust optimization of large-scale wind–solar storage renewable energy systems considering hybrid storage multi-energy synergy. Sustainability. 2023; 16(1): 243.
11. Mao Y, Cai Z, Jiao X, et al. Multi-timescale optimization scheduling of integrated energy systems oriented towards

generalized energy storage services. Scientific Reports. 2025; 15(1): 8549.
12. Xiao Y, Sun W, Sun L. Dynamic programming based economic day-ahead scheduling of integrated tri-generation energy system with hybrid energy storage. Journal of Energy Storage. 2021; 44: 103395.
13. El Hafdaoui H, Khallaayoun A, Al-Majeed S. Controlled non-dominated sorting genetic algorithms for multi-objective optimal design of standalone and grid-connected renewable energy systems in integrated energy sectors. IEEE Access. 2025; 13: 14658–14685.
14. Liu Z, Liu B, Ding X, et al. Research on optimization of energy storage regulation model considering wind–solar and multi-energy complementary intermittent energy interconnection. Energy Reports. 2022; 8(7): 490–501.
15. Dong Z, Qiao H, Li S, et al. Optimizing an Integrated Wind-Solar-Pumped Storage System for Low-Carbon Energy Planning. In: Proceedings of the 2024 IEEE Sustainable Power and Energy Conference (iSPEC); 24–27 November 2024; Kuching, Malaysia.
16. Cameron LJ. Energy 'Access' for Sustainable Development: Enabling Modern Energy Practices in Rural Communities [PhD thesis]. University of Sheffield; 2017.
17. Mao Y, Yu D, Chai B, et al. Feasibility insights into wastewater phosphorus recovery from plant-wide integrated techno-economic and sustainability modeling analysis. Journal of Water Process Engineering. 2025; 75: 107955.
18. Lord FN, Retamal M, Davila F. Strengthening transformative capacities for urban sustainability: A case study of waste reform in Battambang, Cambodia. Urban Transformations. 2024; 6(1): 8.
19. Bamisile O, Cai D, Adun H, et al. Towards renewables development: Review of optimization techniques for energy storage and hybrid renewable energy systems. Heliyon. 2024; 10(19), e37482.
20. Iavorschi E, Milici LD, Taran I, et al. Sustainability of the European Energy System: The Evolution of the Energy Transition, Renewable Energy, and Energy Conservation. Sustainability. 2026; 18(8): 4046.
21. Sharma R, Lopes de Sousa Jabbour AB, Jain V, et al. The role of digital technologies to unleash a green recovery: Pathways and pitfalls to achieve the European Green Deal. Journal of Enterprise Information Management. 2021; 35(1): 266–294.
22. Khalili S, Lopez G, Breyer C. Role and trends of flexibility options in 100% renewable energy system analyses towards the Power-to-X Economy. Renewable and Sustainable Energy Reviews. 2025; 212: 115383.
23. Sinha BR, Sharma RC., Sharma SR. Encyclopaedia of Professional Education. Sarup & Sons; 2003.
24. Conti S, Aiello G, Coco S, et al. Optimization and Machine Learning for Electric Vehicles Management in Distribution Networks: A Review. Energies. 2026; 19(4): 986.
25. Vagnoni E, Gezer D, Anagnostopoulos I, et al. The new role of sustainable hydropower in flexible energy systems and its technical evolution through innovation and digitalization. Renewable Energy. 2024; 230: 120832.
26. Harby A, Schäffer LE, Arnesen F, et al. IEA Hydropower, Annex IX, White Paper No. 1: Flexible Hydropower Providing Value to Renewable Energy Integration. IEA Hydropower; 2019.
27. Opperman JJ, Carvallo JP, Kelman R, et al. Balancing renewable energy and river resources by moving from individual assessments of hydropower projects to energy system planning. Frontiers in Environmental Science. 2023; 10: 1036653.
28. Shahzad S, Jasińska E. Renewable revolution: A review of strategic flexibility in future power systems. Sustainability. 2024; 16(13): 5454.
29. Zhang H, Cao Q, Gao H, et al. Optimum design of a multi-form energy hub by applying particle swarm optimization. Journal of Cleaner Production. 2020; 260: 121079.
30. Jin S, Wang D, Tang P, et al. Flexible Input/Output Port-Based Energy Router for Integrating Offshore Wind Farms through Multiform Power Transmission Technologies. IEEE Transactions on Sustainable Energy. 2026; 1–14.
31. Wu L, Chao P, Li W, et al. A risk assessment method of multi-form transient voltage stabilities for high-proportion renewable energy sending-end power grids. International Journal of Electrical Power & Energy Systems. 2026; 174: 111503.
32. Zhang Z, Jin J, Li S, et al. Research review and development trend analysis of grain multimodal transport with a special emphasis upon China. Agriculture. 2026; 16(5): 592.
33. Osorio-Aravena JC, Aghahosseini A, Bogdanov D, et al. The impact of renewable energy and sector coupling on the pathway towards a sustainable energy system in Chile. Renewable and Sustainable Energy Reviews. 2021; 151: 111557.
34. ur Rehman A, Sanjari MJ, Elavarasan RM, et al. Sustainability-aligned pathways for energy transition: A review of low-carbon energy network solutions. Renewable and Sustainable Energy Reviews. 2026; 226: 116428.
35. Liu M, Chen WA, Gao Y, et al. Comparative Analysis of Battery and Thermal Energy Storage for Residential

Photovoltaic Heat Pump Systems in Building Electrification. Sustainability. 2025; 17(21): 9497.
36. Huang P, Lovati M, Zhang X, et al. Transforming a residential building cluster into electricity prosumers in Sweden: Optimal design of a coupled PV-heat pump-thermal storage-electric vehicle system. Applied Energy. 2019; 255: 113864.
37. Abdur Rehman O, Palomba V, Frazzica A, et al. Enabling technologies for sector coupling: A review on the role of heat pumps and thermal energy storage. Energies. 2021; 14(24): 8195.
38. Onen PS, Mokryani G, Zubo RH. Planning of multi-vector energy systems with high penetration of renewable energy source: A comprehensive review. Energies. 2022; 15(15): 5717.
39. Qu G, Xia H, Liang Q, et al. Current research status and future trends of vibration energy harvesters. Micromachines. 2024; 15(9): 1109.
40. Negro SO, Alkemade F, Hekkert MP. Why does renewable energy diffuse so slowly? A review of innovation system problems. Renewable and Sustainable Energy Reviews. 2012; 16(6): 3836–3846.
41. Kaltschmitt M, Streicher, W, Wiese A. Renewable Energy Systems:Technology, Economics and Environment. Springer; 2007.
42. Lund H. Renewable Energy Systems: A Smart Energy Systems Approach to the Choice and Modeling of Fully Decarbonized Societies. Elsevier; 2024.
43. Schmidt J, Gruber K, Klingler M, et al. A new perspective on global renewable energy systems: Why trade in energy carriers matters. Energy & Environmental Science. 2019; 12(7): 2022–2029.
44. Nosair H, Bouffard F. Flexibility envelopes for power system operational planning. IEEE Transactions on Sustainable Energy. 2015; 6(3): 800–809.
45. Helistö N, Kiviluoma J, Holttinen H, et al. Including operational aspects in the planning of power systems with large amounts of variable generation: A review of modeling approaches. Wiley Interdisciplinary Reviews: Energy and Environment. 2019; 8(5): e341.
46. Abdin AF, Zio E. An integrated framework for operational flexibility assessment in multi-period power system planning with renewable energy production. Applied Energy. 2018; 222: 898–914.
47. Das P, Mathur J, Bhakar R, et al. Implications of short-term renewable energy resource intermittency in long-term power system planning. Energy Strategy Reviews. 2018; 22: 1–15.
48. Jones LE. Renewable Energy Integration: Practical Management of Variability, Uncertainty, and Flexibility in Power Grids. Academic Press; 2017.
49. Zang T, Wang S, Wang Z, et al. Integrated planning and operation dispatching of source–grid–load–storage in a new power system: A coupled socio–cyber–physical perspective. Energies. 2024; 17(12): 3013.
50. Shobrys DE, White DC. Planning, scheduling and control systems: Why can they not work together. Computers & Chemical Engineering. 2000; 24(2–7): 163–173.
51. Liu H, Wang C, Ju P. Review on Resilience Analysis and Enhancement of Integrated Energy Power Systems Considering Dual Carbon Goal. Journal of Electrical Engineering. 2023; 18(2): 108–124.
52. Nagireddi S, Agarwal JR, Vedapuri D. Carbon Dioxide Capture, Utilization, and Sequestration: Current Status, Challenges, and Future Prospects for Global Decarbonization. ACS Engineering Au. 2023; 4(1): 22–48.
53. Salman CA, Li H, Li P, et al. Improve the flexibility provided by combined heat and power plants (CHPs)—A review of potential technologies. e-Prime—Advances in Electrical Engineering, Electronics and Energy. 2021; 1: 100023.
54. Anvari P, Tousi B, Talavat V, et al. A Smart integrated framework for resilience enhancement in distribution networks using multi-energy microgrids and distributed energy resources. Results in Engineering. 2025; 27: 105635.
55. Taghizad-Tavana K, Safari A, Hagh MT, et al. A systematic review of resilience strategies with emphasis on the role of machine learning and quantitative assessment under adverse operating conditions. International Journal of Electrical Power & Energy Systems. 2026; 174: 111472.
56. Shanmugam B. Hydrogen-centric multi-energy systems for high-renewables grids: Technologies, flexibility services, and deployment pathways—A critical review. International Journal of Hydrogen Energy. 2026; 223: 154429.
57. Sun H, Guo Q, Shen X, et al. Energy internet: Redefinition and categories. Energy Internet. 2024; 1(1): 3–8.
58. Datta U, Kalam A, Shi J. A review of key functionalities of battery energy storage system in renewable energy integrated power systems. Energy Storage. 2021; 3(5): e224.
59. Suberu MY, Mustafa MW, Bashir N. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. Renewable and Sustainable Energy Reviews. 2014; 35: 499–514.
60. Sun H, Wang Z, Meng Q, et al. Advancements in hydrogen storage technologies: Enhancing efficiency, safety, and economic viability for sustainable energy transition. International Journal of Hydrogen Energy. 2025; 105: 10–22.

61. Aslam MA, Mustaqeem M, Abbas MS, et al. Hydrogen Revolution: Advances in Catalytic Ammonia Decomposition. Clean Energy Technologies. 2025; 1(1): 49–69.
62. Lin X, Song J, Jin X (editors). Introduction to Carnot Battery. In: Integrated Energy Systems with a Carnot Battery: A Pathway to Low-Carbon Energy Systems. CRC Press; 2026. pp. 1–21.
63. Bagherzadeh L, Kamwa I, Delavari A. Coupling energy management of power systems with energy hubs through TSO–DSO coordination: A review. International Journal of Emerging Electric Power Systems. 2025; 26(2): 183–222.
64. Liu C, Zhang X, Said Z. Status and Evaluation of Energy Storage Technology: Advances and Challenges in Phase Change Materials. In: Wang Z, He H (editors). Energy and Environmental Technologies Towards Carbon Neutrality. Royal Society of Chemistry. 2026. 4, pp. 356–401.
65. Xu J, Wang P, Bai Z, et al. Sustainable moisture energy. Nature Reviews Materials. 2024; 9(10): 722–737.
66. Zaini FA, Sulaima MF, Razak IAW, et al. A Review on the Applications of PSO-Based Algorithm in Demand Side Management: Challenges and Opportunities. IEEE Access. 11: 53373–53400.
67. Zhang Y, Wu S, Lv Z, et al. Optimization configuration of hybrid energy storage in integrated energy systems. Applied Energy. 2026; 424: 128394.
68. Li F, Wang H, Liu D, et al. A Review of Multi-Temporal Scale Regulation Requirements of Power Systems and Diverse Flexible Resource Applications. Energies. 2024; 18(3): 643..
69. Liu Z, Li D, Wang W, et al. A review of the research on the wide-band oscillation analysis and suppression of renewable energy grid-connected systems. Energies. 2024; 17(8): 1809.
70. Kumar A, Yanamala Y, Torshin I. Revolutionizing Data Management: Next-Generation Enterprise Storage Technologies for Scalability and Resilience. International Journal of Advanced Engineering Technologies and Innovations. 2024; 6(2): 105–135.
71. Amir M, Deshmukh RG, Khalid HM, et al. Energy storage technologies: An integrated survey of developments, global economical/environmental effects, optimal scheduling model, and sustainable adaption policies. Journal of Energy Storage. 2023; 72: 108694.
72. Lv C, Wang X, Xue S, et al. Research on coupling risk assessment method of industrialized urban area based on information diffusion and extension grey clustering model. PLoS ONE. 2025; 20(5): e0322700. https://doi.org/10.1371/journal.pone.0322700
73. Son YG, Oh BC, Acquah MA, et al. Multi energy system with an associated energy hub: A review. IEEE Access. 2021; 9: 127753–127766.
74. Xu Q, Ji Y, Qin L, et al. Evaluation of redox flow batteries goes beyond round-trip efficiency: A technical review. Journal of Energy Storage. 2018; 16: 108–115.
75. Smdani GG, Islam MR, Yahaya ANA, et al. Performance evaluation of advanced energy storage systems: A review. Energy & Environment. 2023; 34(4): 1094–1141.
76. Lin X, Song J, Zhong W (editors). Integrated Energy Systems with a Carnot Battery: A Pathway to Low-Carbon Energy Systems. CRC Press; 2026.
77. Zulu MLT, Carpanen RP, Tiako R. A comprehensive review: Study of artificial intelligence optimization technique applications in a hybrid microgrid at times of fault outbreaks. Energies. 2023; 16(4): 1786.
78. Hong Y, Huang H, Xing Q. Practical Dilemmas and Coping Strategies of Designing for Rural Areas in Colleges and Universities from the Perspective of System Theory—Taking Guangdong as an Example. In: Hussain RR, Hu B, Kakooei S, et al. (editors). 2025 6th International Conference on Urban Construction and Management Engineering (ICUCME 2025), Proceedings of the 2025 6th International Conference on Urban Construction and Management Engineering (ICUCME 2025); 11–13 May 2025; Qingdao, China. Atlantis Press; 2025. pp. 275–291.
79. Kaushal RK, Raveendra K, Nagabhooshanam N, et al. Fault prediction and awareness for power distribution in grid connected res using hybrid machine learning. Electric Power Components and Systems. 2024; 1–22.
80. Karthikeyan G, Jagadeeshwaran A. Enhancing solar energy generation: A comprehensive machine learning-based PV prediction and fault analysis system for real-time tracking and forecasting. Electric Power Components and Systems. 2024; 52(9): 1497–1512.
81. Ożadowicz A. Modeling and Simulation Tools for Smart Local Energy Systems: A Review with a Focus on Emerging Closed Ecological Systems' Application. Applied Sciences. 2025; 15(16): 9219.
82. Zhu H, Wang X, Wen Y, et al. A review of integrated energy system modeling and operation. Applied Energy. 2025; 400: 126572.
83. Barrera-Singaña C, Comech MP, Arcos H. A Comprehensive Review on the Integration of Renewable Energy through

Advanced Planning and Optimization Techniques. Energies. 2025; 18(11): 2961.
84. Ghahari S. Integrated Energy Management for Mission-Critical Environments: A Review of Market-Based Trading Mechanisms and Renewable Integration for Enhancing Operational Continuity and Sustainability. https://doi.org/10.2139/ssrn.5368433
85. Pourmirza Z, Couraud B, Bozdal M, et al. Cyber-physical multi-energy systems: Towards an integrated energy system—A review. Renewable and Sustainable Energy Reviews. 2026; 239: 117112.
86. Xu H. 'Sustainability' of What, for Whom? Unfolding China's Sustainability Transitions and Green Modernisation [PhD thesis]. The Australian National University; 2022.
87. Soudagar MEM, Rao BM, Mohanavel V, et al. Hydrogen-electricity-heat sector Coupling: Review of integrated models, control strategies, challenges, and future research directions. Renewable and Sustainable Energy Reviews. 2026; 231: 116756.
88. Gunathilake C, Soliman I, Panthi D, et al. A comprehensive review on hydrogen production, storage, and applications. Chemical Society Reviews. 2024; 53(22): 10900–10969.
89. Pourrahmani H, Madi H, Van Herle J. The Decentralized Hydrogen Revolution Using Artificial Intelligence, Internet of Things, and Blockchain. Elsevier; 2025.
90. Joshua SR, Park S, Kwon K. H2 URESONIC: Design of a Solar-Hydrogen University Renewable Energy System for a New and Innovative Campus. Applied Sciences. 2024; 14(4): 1554.
91. Li H, O'Brien W, Loftness V, et al. A critical review of use cases and insights from a large dataset of smart thermostats. Advances in Applied Energy. 2025; 19: 100236.
92. Korovushkin V, Boichenko S, Artyukhov A, et al. Modern optimization technologies in hybrid renewable energy systems: A systematic review of research gaps and prospects for decisions. Energies. 2025; 18(17): 4727.
93. Berjawi A, Walker S, Patsios C, et al. An evaluation framework for future integrated energy systems: A whole energy systems approach. Renewable and Sustainable Energy Reviews. 2021; 145: 111163.
94. Khan A, Bressel M, Davigny A, et al. Comprehensive review of hybrid energy systems: Challenges, applications, and optimization strategies. Energies. 2025; 18(10): 2612.
95. Yaser AZ, Tamunaidu P, Lamaming J (editors). Sustainable Reuse and Recycling of Agro-Industrial Effluent. CRC Press; 2026.
96. Sanjalawe Y, Ai-E' Mari S, Fraihat S, et al. AI-Powered Smart Grids in the 6G Era: A Comprehensive Survey on Security and Intelligent Energy Systems. IEEE Open Journal of the Communications Society. 2025; 6: 7677–7719.
97. Asadi S, Naeini HK, Hassanlou D, et al. AI-Powered Digital Twin Frameworks for Smart Grid Optimization and Real-Time Energy Management in Smart Buildings: A Survey. Computer Modeling in Engineering & Sciences (CMES). 2025; 145(2): 1259–1301.