

Review

Overview of Iron Energy Utilization: Update Status and Prospective Development

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Abstract

Under the vision of carbon neutrality, the global energy system urgently requires storable, transportable, and tradable zero-carbon carriers. Iron, due to its high crustal abundance, low cost, environmentally friendly reaction products, and ease of closed-loop cycling, is being reconsidered as a potential “metallic energy” alternative to fossil fuels. This paper systematically reviews the conceptual evolution, scientific lineage, and paradigm shift logic of iron-based energy within the framework of dual pathways: combustion and electrochemistry. On the combustion front, a multi-level understanding has been established—ranging from microscopic reaction mechanisms to macroscopic flame propagation, and from unit combustors to diversified thermal power systems—laying a methodological foundation for an integrated “solid fuel–thermal–power” approach. In parallel, the electrochemical pathway has developed both liquid and solid routes, integrating energy storage, pollution control, and resource recovery within a single device through multi-valent redox reversibility, thereby expanding the concept of generalized energy storage under the “battery-as-factory” paradigm. Current research is shifting its focus from single performance metrics toward synergistic optimization of efficiency, lifespan, cost, safety, and environmental impact, marking a transition in technological paradigm from “material trial-and-error” to “mechanism design.” Looking forward, to advance iron energy beyond the experimental validation stage, it is imperative to establish a cross-scale, closed-loop scientific characterization system, develop recycling strategies with low entropy and low energy consumption, and deeply integrate with renewable electricity, hydrogen, and high-temperature heat sources to form spatiotemporally transferable zero-carbon energy systems. In this way, iron may integrate into global energy trade as a “metallic energy in specific scenarios like ports/islands,” offering a scalable, hydrocarbon-independent technological option for achieving carbon neutrality.



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1. Introduction

1.1. The Need for Clean Recyclable Fuels

In the context of contemporary societal diversification, energy, as a key driver of sustained economic, social, and human civilization progress, is of undeniable importance. From gas cooking to boiler-powered electricity generation, nearly every aspect of human life and production relies on energy. The stable supply and rational utilization of energy

profoundly influence not only the pace and quality of economic growth in countries worldwide but are also closely linked to social stability and the quality of life of their populations. It can be said that energy serves as the foundation for all economic activity and wealth creation. For instance, an average citizen in an energy-abundant country utilizes approximately 80 times the amount of energy generated by their own metabolism—a feat made possible primarily through the use of fossil fuels [1].

The core momentum of the world economy today stems from the extraction, circulation, and consumption of fossil fuels, largely due to their low cost, abundant reserves, high energy density, capability for high-power combustion in internal combustion engines, ease of transportation, and relatively low handling risks. Their substantial energy density can be illustrated by the fact that the chemical energy contained in a piece of anthracite coal the size of an adult's fingernail, when combusted with air, is equivalent to the potential energy change of 1000 L of water falling from a height of 30 m.

According to the 2025 Statistical Review of World Energy (seen in Figure 1), fossil fuels (oil, coal, and natural gas) continue to underpin the global energy system, accounting for over 85% of energy consumption [2]. However, carbon dioxide emissions from fossil fuel combustion have become a major driver of global warming. To mitigate climate change, the energy system must transition from a fossil fuel-based foundation to a structure based on zero-carbon renewable energy sources, while also addressing the potential constraints that resource depletion may impose on long-term economic growth. Although biofuels have attracted significant attention, they are constrained by the low energy and power density inherent to photosynthesis, making it difficult for them alone to fully replace fossil fuels in a deeply decarbonized future [3]. By fully leveraging hydrogen energy, hydropower, solar, wind, and geothermal energy, and ultimately deploying clean thermonuclear technology, reliance on fossil fuels for electricity production could, in theory, be entirely eliminated [4]. And green hydrogen production serves as a pivotal solution for deep decarbonization across sectors while mitigating the intermittency of renewable energy [5].

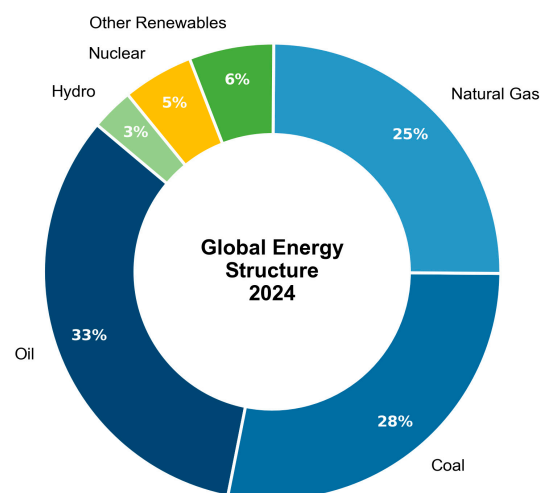


Figure 1. Global energy structure.

Even more challenging is the substitution of fossil fuels in their roles as tradable energy commodities and transportation fuels. Even if electricity is derived from clean sources, it still cannot be stored, transported, or traded on a large scale as conveniently as hydrocarbons. Therefore, a low-carbon future urgently requires storable and transportable renewable energy carriers to achieve the spatial and temporal decoupling of primary energy from end-use demand.

Internal combustion engines (ICEs), characterized by their high power density and utilization of high-energy density hydrocarbon fuels, have become the core technology powering modern transportation [6]. From automobiles and railway locomotives to ships and jet aircraft, their power sources rely on this system. Consequently, to fully replace fossil fuels in terms of performance, it is essential to develop clean energy carriers and corresponding power systems that match both the energy density and power density of their fossil-based counterparts. Currently, few existing solutions can simultaneously achieve the dual high-density characteristics of hydrocarbon fuels and ICEs across most application scenarios. A future low-carbon society will require more candidate carriers with comparable energy and power densities to cover the diverse range of applications currently dominated by fossil fuels.

1.2. Hydrogen

Over recent decades, hydrogen produced from renewable electricity has been widely regarded as a versatile, carbon-free energy medium for the future, serving energy storage and long-distance transmission needs [7]. Its high specific energy, strong chemical reactivity, compatibility with various energy conversion devices (such as internal combustion engines, gas turbines, and fuel cells), and near-zero tailpipe emissions have drawn significant attention.

However, the hydrogen economy has yet to materialize, primarily due to two major obstacles: the extremely low volumetric energy density of gaseous hydrogen, and the persistent risks of combustion and explosion during storage, transportation, and refueling [8,9]. Even when cryogenically liquefied, its volumetric energy density remains an order of magnitude lower than that of conventional hydrocarbon fuels like gasoline [10]. The processes of liquefaction or high-pressure compression are themselves energy-intensive. Furthermore, vacuum-insulated Dewar vessels are bulky and cannot prevent boil-off losses during prolonged storage, further reducing overall energy efficiency.

Alternative strategies for solid or liquid hydrogen storage—such as metal hydrides, organic liquid carriers, carbon nanotubes, and porous metal–organic frameworks—have similarly failed to meet the U.S. Department of Energy’s 7.5 wt% storage target under ambient conditions [11,12]. A common limitation is the necessity to incorporate substantial inert “dead mass” that does not participate in the oxidation reaction. This ballast, used to bind hydrogen via chemical bonding, surface adsorption, or physical encapsulation, results in a system-level hydrogen storage density that struggles to surpass that of liquid hydrogen. A feasible pathway remains elusive in the near term.

1.3. Solar Hydrocarbon Fuels

Recent studies propose using renewable electricity or solar energy as primary sources to synthesize hydrocarbon fuels (solar fuels) directly by coupling atmospheric CO₂ with hydrogen [13]. This approach offers the advantage of compatibility with existing fuel storage, transportation, trading systems, and power generation infrastructure, thereby avoiding the need for extensive rebuilding [14]. However, similar to biofuels, the solar hydrocarbon route faces the limitation of extremely dilute CO₂ sources (≈ 400 ppm) in the atmosphere [15]. While the atmosphere serves both as the carbon sink after fuel combustion and the carbon source for production, CO₂ must first be concentrated before it can be used in the synthetic cycle. This capture step requires additional equipment and energy input, significantly increasing costs [16] and reducing the system’s net energy gain due to the relatively low efficiency of the carbon cycle.

If flue gas from fossil fuel power plants is used as the CO₂ source [17], fuel production costs may be reduced, but combusting these fuels in end-use internal combustion engines

merely re-releases the previously captured fossil-derived CO₂, thus failing to achieve net low carbon emissions [16]. Any energy system that ultimately emits CO₂ into the atmosphere—even if the carbon is initially captured from the air—cannot easily achieve net-zero or negative emissions.

An ideal closed-loop low-carbon or zero-carbon fuel should combine low cost and high energy efficiency to enhance both economic viability and systemic sustainability. Here, the term “fuel” broadly refers to any reduced substance that can be oxidized (typically reacting with oxygen) to release energy [13]. Such fuels produced from clean energy sources are classified as secondary energy carriers or energy vectors. For any new fuel to meet societal demands, it must surpass existing battery or hydrogen-based solutions in both energy density and power density. These considerations point toward one promising direction: prioritizing the development of non-carbon-based fuels whose combustion products are solid. These solid oxides can be captured locally and regenerated in a recyclable manner.

However, the fundamental bottlenecks of hydrogen and solar fuels—specifically their low volumetric density and high handling risks—reveal a critical gap in the search for viable zero-carbon carriers. This necessitates a transition to iron fuel, which uniquely resolves the “energy density–safety–cyclability” trilemma. Unlike existing gaseous or synthetic alternatives, iron offers an irreplaceable combination of high volumetric density, inherent safety during transport, and a fully reversible chemical cycle. By bridging these technical trade-offs, iron fuel emerges as the optimal medium for broad-scale energy storage, providing the stability and efficiency that current decarbonization pathways lack.

1.4. Metal Fuels

Within the periodic table, only a handful of carbon-free candidate energy carriers can compete directly with hydrocarbon fuels in terms of both mass and volumetric energy storage. Metallic energy represents a long-underestimated yet highly promising class of zero-carbon cyclic fuels [18]. Their advantage stems from highly exothermic reactions with oxygen from air, producing non-toxic and stable solid oxides.

As shown in Table 1, the volumetric energy density of certain metals upon complete combustion in air already surpasses that of conventional fossil fuels like gasoline; among them, boron exhibits a particularly superior energy density. Due to its exceptionally high energy density, boron was historically investigated as an additive for propellants or explosives [19] and has recently been re-evaluated as a recyclable solar fuel for energy storage [20]. While beryllium also possesses high energy density [21,22], its oxide is highly toxic, limiting its widespread application [23]. Aluminum, magnesium, and iron are abundant, offering high volumetric energy density and favorable specific energy, making them suitable both as metal fuels and as anode materials for batteries. Furthermore, the energy densities of these metals comprehensively exceed those of biomass (e.g., wood chips, pellets), coal, and compressed/liquefied natural gas currently traded in global energy markets, offering new pathways for establishing zero-carbon energy cycles.

Among these metallic fuels, aluminum faces the issue of its oxide product forming a passivating layer that inhibits further reaction; magnesium and lithium suffer from low volumetric energy density; beryllium produces toxic oxides; and boron is expensive and primarily reserved for military applications [24]. In comparison, iron possesses high volumetric energy density, non-toxic and readily recyclable reaction products, low cost, and relatively stable chemical and physical properties, making it suitable for long-distance transportation within energy trading networks [25]. Consequently, iron powder emerges as a clean energy carrier capable of replacing fossil fuels as can be seen in Table 2. It can store clean energy, such as wind and solar power, through the reduction of its oxides, and efficiently convert this energy into heat via combustion in air or water. Simultaneously, the

iron oxide generated after combustion can be utilized in the production of high-purity iron and other high-grade metal materials or can be reduced back into iron powder, thereby establishing a sustainable closed-loop utilization system.

Based on a review of domestic and international literature concerning iron-based energy utilization, this paper presents a conceptual synthesis of the research landscape surrounding iron in key areas, including combustion reaction kinetics, the energy density of iron-fueled cells, and the feasibility of iron energy cycles. Rather than providing exhaustive technical evaluations, the emphasis is placed on integrating established findings into a coherent framework for understanding the potential role of iron as an energy carrier. The paper identifies critical bottlenecks hindering the transition from laboratory-scale proof-of-concept to industrial-scale application and proposes broadly verifiable improvement pathways alongside context-specific deployment strategies. This work aims to serve as a foundational reference for designing zero-carbon energy systems utilizing iron as a strategic energy vector.

Table 1. Comparison of energy density between metal fuel and hydrocarbon fuel (ASTM E711 [26]).

Material Sorts	Melting Point/K	Boiling Point/K	Reacting with Oxygen	
Metal			Mass energy density/MJ·kg ^{−1}	Volume energy density/MJ·L ^{−1}
Fe	1811	3273	7.397	58.14
Al	933	2767	31.054	83.847
Mg	923	1366	24.761	43.085
Li	454	1620	42.998	22.79
Be	1560	2744	62.700	116.00
B	2450	3931	267.06	135.00
Hydrocarbon				
Gasoline		300–600	44–46	32–34
Methanol		338	19.7–22.7	15.9–17.9
Ethanol		352	26.8–29.7	21.1–23.4

Table 2. Comparative analysis of zero-carbon energy carriers.

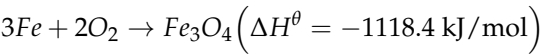
Energy Carrier	Gravimetric Energy Density (MJ/kg)	Volumetric Energy Density (MJ/L)	Round-Trip Efficiency (RTE)	Estimated Cost (\$/kWh Delivered)	Storage/Transport Maturity
Iron Powder (Fe)	~7.4	~113.0	35–50%	\$0.05–\$0.15	High (Solid/Stable)
Liquid Hydrogen (LH ₂)	~120.0	~8.5	30–40%	\$0.20–\$0.50	Complex (Cryogenic)
Ammonia (NH ₃)	~18.6	~12.7	20–35%	\$0.12–\$0.30	Moderate (Toxic/Pressure)
Synthetic Fuels (e-Methanol)	~19.9	~15.8	10–20%	\$0.30–\$0.80	High (Drop-in)

1.5. Terminology Definition

1.5.1. Metallic Energy and Iron as an Energy Carrier

“Metallic energy” refers to the chemical potential energy stored within refined metals, which can be released through exothermic oxidation reactions. In this manuscript, iron energy is defined not as a primary energy source, but as a circular energy carrier.

Thermodynamic Basis: The energy density of iron is dictated by its Gibbs free energy change (ΔG) during oxidation. For the primary reaction:



The “stored” energy is the difference in chemical potential between the reduced state (pure Fe) and the oxidized state (Fe_2O_3 or Fe_3O_4). Unlike fossil fuels, the product of combustion is a solid oxide that remains localized and recoverable.

Mass Flow Attribute: In an ideal mass flow analysis, the iron medium follows a closed-loop trajectory:

Reduction (Energy Charging) → Transport → Combustion (Energy Release) → Collection → Recycle

The total mass of the iron element (m_{Fe}) remains constant throughout the cycle, functioning as a “renewable vessel” for electrons provided by primary renewable sources (solar, wind, etc.).

1.5.2. Zero-Carbon Cycle Fuel

A zero-carbon cycle fuel is defined as a fuel whose utilization results in net-zero CO_2 emissions across its entire lifecycle by decoupling the energy release from carbon-based chemistry.

Essential Attributes: Unlike “carbon-neutral” fuels (e.g., biomass), which still involve the flux of CO_2 into and out of the atmosphere, iron energy is carbon-free at the molecular level.

1.5.3. Iron Oxide Reduction Pathways

To achieve a closed-loop, zero-carbon system, the reduction of iron oxide (Fe_2O_3 or Fe_3O_4) must be decoupled from fossil fuels. This section evaluates the trade-offs between the two primary technological archetypes [27]. And the differences between electrochemical and thermochemical pathways can be seen in Table 3.

Table 3. Comparative parameters between electrochemical and thermochemical.

Parameter	H ₂ -Based Thermochemical (H ₂ -DRI)	Aqueous Electrochemical (Electrowinning)
Specific Energy Consumption	3.8–4.2 MWh/ton-Fe	2.9–3.5 MWh/ton-Fe
Reduction Efficiency	60–70%	75–85%
Operating Temperature	800–1000 °C	80–110 °C
Sintering Risk	High: High temps lead to particle necking and surface area loss (<0.1 m ² /g).	Low: Low-temp process preserves morphology; risk of dendritic growth instead.
Purity/Impurities	Dependent on ore grade; requires high-grade magnetite (>65% Fe).	High selectivity; can handle lower grade ores by dissolving Fe selectively.
Energy Loss Mechanism	Sensible heat in off-gases and incomplete H ₂ utilization.	Ohmic losses and oxygen evolution reaction (OER) overpotential.

Technical Bottlenecks in the Reduction Cycle

Sintering and Surface Area Degradation: High-temperature thermochemical reduction often leads to sintering, where iron particles partially fuse. This reduces the specific surface area, significantly lowering the reactivity and “ignitability” of the iron powder in the subsequent combustion phase. A critical challenge is maintaining particle morphology over multiple cycles without resorting to energy-intensive mechanical milling.

Energy Loss Analysis: The round-trip efficiency is primarily burdened by the latent heat of reduction and the inefficiencies of hydrogen production (if using H₂-DRI). In electrochemical pathways, the overpotential at the anode and the energy required to maintain molten salt temperatures represent the primary sinks.

Impurity Accumulation: In a closed-loop system, impurities (e.g., silica, alumina) from the combustion environment or the reduction vessels can accumulate. These “dead weights” do not contribute to energy release but increase the energy required for heating

and transport. The manuscript must address the refinement threshold—the point at which accumulated impurities necessitate a high-energy purification step [28].

2. Iron Combustion

Current research on the iron powder combustion methodology exhibits two distinct yet complementary branches. The first focuses on the single-particle scale, utilizing advanced diagnostic techniques such as high-speed imaging, micro-gravity suspension, and numerical coupling to decipher the cross-scale mechanisms of surface oxidation and combustion. This enables the construction of single-particle combustion models that integrate diffusion, kinetics, and radiative heat transfer. The second branch investigates the macroscopic behavior of particle clouds, employing experimental setups like constant-volume combustion bombs, flat-flame burners, and fluidized beds to acquire key parameters including flame propagation speed, combustion temperature fields, apparent activation energy, and stability criteria, thereby establishing apparent kinetic models based on continuum assumptions. Together, these approaches form a comprehensive theoretical framework for iron powder combustion, spanning from microscopic mechanisms to macroscopic performance. This section will systematically elaborate on the foundational research concerning iron powder combustion mechanisms and the state-of-the-art in combustor design, which directly determines flame stability, burnout efficiency, and system longevity. It aims to provide a quantifiable theoretical basis and data benchmark for the structural optimization of combustors, reaction pathway control, and the design of closed-cycle processes, thereby laying the groundwork for the scalable application of iron-based zero-carbon energy systems. Figure 2 shows the framework of this section.

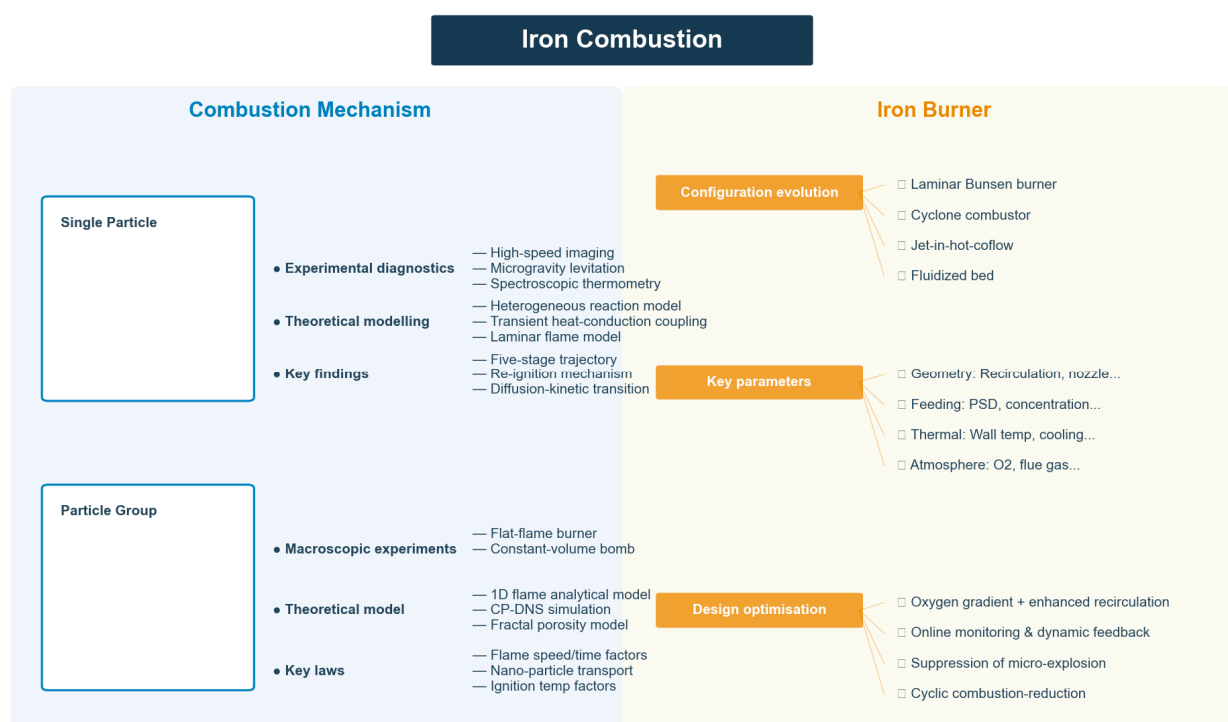


Figure 2. Framework diagram of iron powder combustion research.

2.1. Combustion Mechanism

Current research on iron powder combustion mechanisms exhibits two distinct methodological branches. The first focuses on single particles, utilizing techniques such as high-speed imaging, micro-gravity suspension, and coupled numerical simulations

to elucidate the cross-scale coupling mechanisms of surface oxidation and combustion. This approach enables the development of single-particle combustion models that incorporate diffusion, kinetics, and radiative heat transfer. The second branch concentrates on the macroscopic behavior of particle clouds, employing experimental setups including constant-volume combustion chambers, flat-flame burners, and fluidized beds to measure parameters such as flame propagation speed, combustion temperature fields, apparent activation energy, and stability criteria. Consequently, apparent kinetic models based on continuum assumptions are established. These two research strands complement each other, collectively forming a theoretical framework for iron powder combustion that spans from microscopic mechanisms to macroscopic performance.

2.1.1. Single Particle Combustion

Single-particle-scale research serves as the foundation for elucidating the combustion mechanisms of iron-based fuels, and provides critical validation for particle-cloud combustion theories and burner design. At this scale, studies have comprehensively covered the entire process from ignition, melting, and phase transition to oxide condensation, establishing a tripartite research paradigm integrating experimental diagnostics, theoretical modeling, and numerical verification.

The combustion of single iron particles is a complex process governed by the interplay of kinetics, diffusion, and phase changes. Bidabadi et al. [29] provided a foundational framework for understanding this by pioneering a model that couples transient heat conduction, diffusion, and surface reactions to solve for particle temperature evolution. Building on this theoretical groundwork, experimentalists like Li Shen et al. [30] used high-speed imaging to demystify the process, identifying five distinct combustion stages: heating, melting, intense combustion, cooling, and re-ignition. They linked re-ignition to the rupture of the surface oxide shell and found combusted particles form hollow microspheres, a crucial morphological insight.

To further quantify the dynamics, Li Tao et al. [31] then applied synchronized imaging techniques, establishing melting time scales with particle diameter as $\tau_m \propto d_p^{1.6}$. More importantly, their gas-phase kinetic calculations revealed that FeO oxidation contributes over 18% to the total heat release, a finding that directly challenged the traditional assumption of surface oxidation dominance.

This mechanistic insight was expanded by Ning et al. [32], who developed a sophisticated single-particle generator to probe the controlling mechanisms. Their work revealed a clear transition in combustion control from external to internal oxygen diffusion, pinpointing the critical threshold at a Damköhler number of $Da \approx 1.2$. The same team [33] then leveraged high-resolution spectro-thermometry to probe the nano-scale products of combustion. They discovered that when the particle surface temperature exceeds 2300 K, it triggers the in situ formation of nano-oxide clouds (10–50 nm), a critical finding for controlling PM_{2.5} emissions. In subsequent research, Ning et al. [34] employed laser ignition to systematically study the effect of oxygen concentration, showing peak temperatures rose from 2450 K to 2750 K as O₂ increased from 15% to 40%. Their thermodynamic analysis clearly identified $\text{Fe(g)} \rightarrow \text{FeO(g)} \rightarrow \text{FeO}_{1.5}\text{(s)}$ as the pathway for nano-oxide formation.

While the above studies focus on single particles, the principles also inform our understanding of collective combustion in dust clouds. For instance, Palečka [35] conducted microgravity experiments showing that flame propagation speed remained constant at 0.38 m/s despite varying combustion times, providing key experimental validation for discrete flame theory in metal dust clouds. To accurately simulate these intricate processes, advanced modeling efforts are essential. Thijs et al. [36] improved a Lagrangian point-particle model by incorporating boundary layer resolution and Stefan flow, which

reduced predicted particle heating times by ~25% and highlighted the significant error from simplifying gas-phase radiation. At the system level, Gool [37] proposed a chemical equilibrium-based laminar flame model for iron/air mixtures. This model successfully predicted that the formation and decomposition of Fe_3O_4 contributes 26% of the total heat release and achieved flame speed predictions with less than 8% error, validating the use of equilibrium assumptions in certain metal flame scenarios.

Figure 3 demonstrates the framework of single iron particle combustion research.

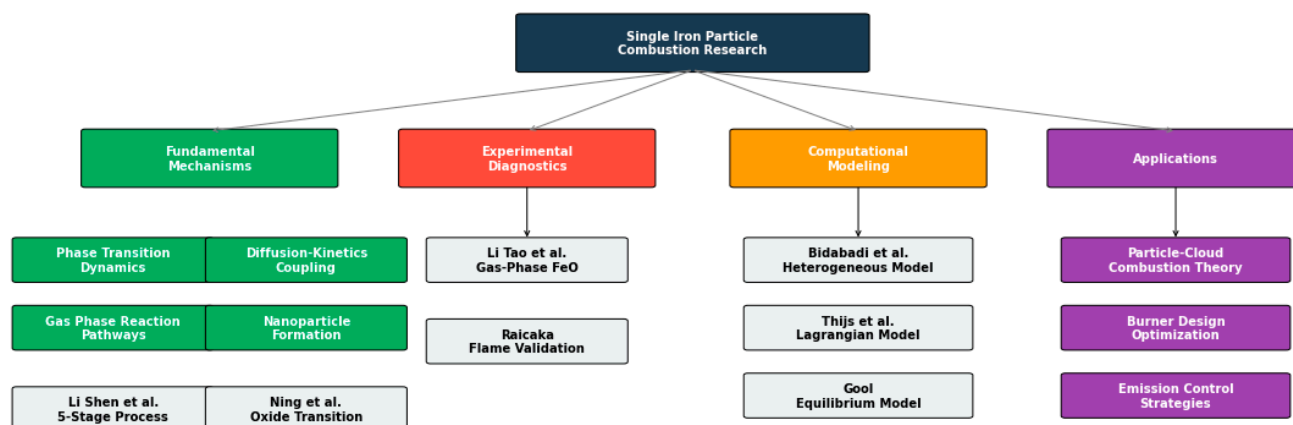


Figure 3. Single iron particle combustion research framework.

2.1.2. Particle Group Combustion

Research on iron powder particle-cloud combustion follows a framework connecting “macroscopic flame behavior–mesoscopic particle-cloud dynamics–microscopic single-particle reaction,” employing cross-validation through experimental diagnostics, theoretical modeling, and multi-scale simulations to systematically analyze key processes such as flame propagation, ignition, deposition, micro-explosion, and nano-byproduct generation.

Mohsen et al. [38] established foundational scaling laws for premixed iron dust clouds, showing that for micro-sized particles, burnout time scales with the square of the diameter ($t_e \propto d^2$) while laminar flame speed is inversely proportional to it ($S_l \propto d^{-1}$). Building on these macroscopic observations, studies have delved into the particle-level dynamics that govern group ignition and combustion. Mi et al. [39] quantitatively showed that the critical ignition temperature is controlled by the relative oxide layer thickness, with ignition delay scaling as $\tau_{\text{ign}} \propto d^2$. Complementarily, Wan et al. [40] demonstrated that increased particle porosity significantly enhances collective reactivity by reducing ignition temperature and delay.

The role of turbulence in shaping group combustion was clarified by Luu et al. [41], whose direct simulations revealed that turbulence enhances particle heating and ignition, with combustion concentrated in particle clusters and ultimately limited by local oxygen availability. A key aspect of group combustion is the transformation of particles and the formation of byproducts. Huang et al. [42] and Peng et al. [43] investigated micro-explosions, identifying them as frequent, oxygen-dependent events that fragment particles and sharply alter local temperatures. Furthermore, Nguyen et al. [44] modeled the condensation of supersaturated iron vapor into nanoparticles, identifying particle temperature as the key control parameter and thermophoresis as the dominant transport mechanism in the cloud. Poletaev et al. [45] confirmed that the combustion environment (premixed vs. diffusion flame) directly influences the combustion mode and the resulting particle size distribution. Finally, research addresses critical application-oriented challenges. Chen et al. [46] identified cyclic deactivation as a key limit on energy release efficiency in redox cycles, while Lee et al. [47] linked the deposition of molten particles to surface thermal properties,

a critical factor for combustor longevity. Framework of particle cloud combustion research can be seen in Figure 4.

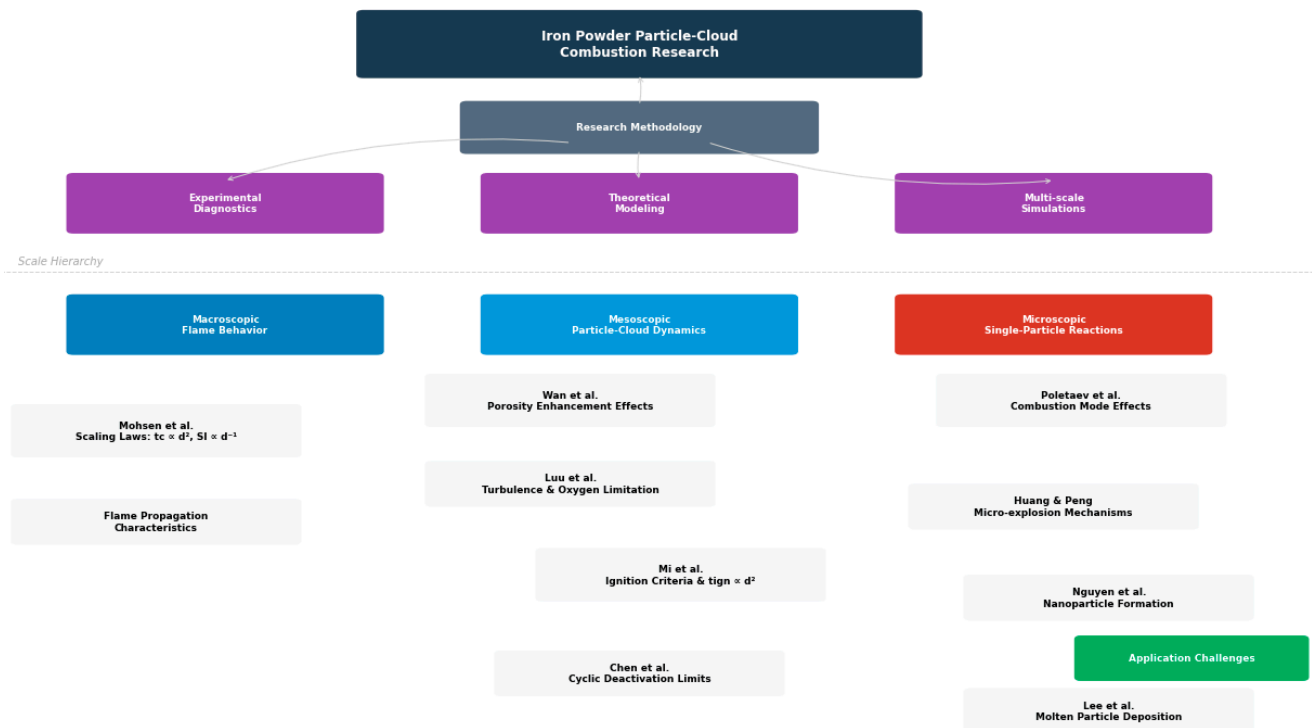


Figure 4. Framework diagram for particle cloud combustion research.

2.2. Iron Burner

(1) Research progress at home and abroad

Combustors serve as the core hardware for the controlled release and efficient conversion of chemical energy in iron powder, where the organization of the flow field, fuel supply, heat and mass coupling, and product capture methods directly determine flame stability, burnout efficiency, and system lifespan. The second part will systematically review the evolution of combustor configurations tailored for iron powder flame characteristics in recent years: ranging from laminar Bunsen burners and cyclone combustors to nozzle-based two-phase flow reactors. It will focus on critiquing the influence of geometric parameters, powder feeding strategies, recirculation zone scale, and wall thermal boundary conditions on iron particle ignition, micro-explosion suppression, and oxide deposition, while summarizing design principles and optimization pathways to provide a transferable framework for subsequent engineering scale-up [48].

Research on iron powder burners focuses on optimizing combustion efficiency, stability, and emissions by investigating combustor design, particle dynamics, and operational parameters.

Combustion Characterization & Particle Dynamics: Huang et al. [49] used high-speed holography in a Bunsen burner, showing that high oxygen concentrations cause intense combustion to eject particles radially, creating an uneven distribution and confirming particle swelling. Hameete et al. [50] designed a jet-hot coflow burner, finding that larger particles have higher ignition failure rates due to short residence times, and that dust concentration has little effect on ignition temperature.

Combustor Performance & Optimization: In Metal Cyclone Combustor (MC2) studies, Prasadha [51] identified stable flame conditions (e.g., $O_2 > 13.5\%$, particle spacing ≤ 0.5 mm) and found that higher equivalence ratios co-inhibit nanoparticle and NO_x emissions.

Sohrabi et al. [52] demonstrated that larger particles (50 μm) achieve 94% combustion efficiency by increasing residence time, while sub-20 μm particles perform poorly (72% efficiency). D  bal [53] constructed a chemical reactor network model for a swirl combustor, revealing that evaporation is low (<4%) and that oxygen distribution and gas temperature are the dominant factors controlling NO_x and nanoparticle emissions. While the optimization of MC2 and swirl combustors demonstrates high combustion efficiency and reduced NO_x formation, the industrial transition requires a critical assessment of the associated occupational and environmental hazards. Specifically, the high efficiency of larger particles must be weighed against the inherent dust explosion risks and inhalation hazards (particulate exposure) during bulk handling and storage. Furthermore, the low nanoparticle emissions reported in reactor models depend heavily on the efficacy of capture systems; any failure in material recovery not only creates a mass balance penalty that undermines the economic viability of the fuel cycle but also risks environmental contamination through fugitive metal dust. Consequently, the technical benefits of iron-based combustion are only industrially relevant if integrated with robust containment strategies, secondary filtration, and comprehensive safety protocols for handling metallic fuels.

Operational Challenges: Agglomeration & Defluidization: Fluidized bed studies highlight key limitations. Shao et al. [54] visually identified the onset of particle sticking at 673–773 K and critical defluidization at 923–973 K. Zhong et al. [55] found that defluidization temperature decreases with gas velocity and is significantly lowered by CO-60 due to chemical adsorption. Stevens et al. [56] observed severe agglomeration after the first combustion cycle in a cyclone combustor, requiring manual grinding to restore fluidity.

Propulsion Application: Wang et al. [57] validated a numerical model for a nano-iron powder rocket engine, confirming that particle size (0.4–1.0 μm) and condensate content are critical performance parameters, with 50 nm particles showing excellent agreement between predicted and measured thrust.

Tree diagram for iron burner research can be seen in Figure 5.

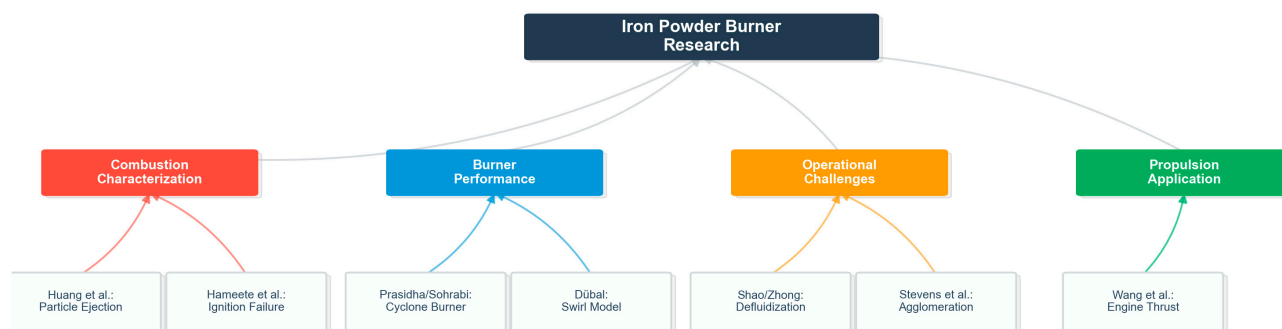


Figure 5. Tree diagram for iron burner research.

(2) Progress of Our Research

Building upon fluidized bed technology, we conducted in-depth investigations into the fluidization of iron powder, systematically studying key parameters such as fluidization pressure and velocity during the process. Utilizing a self-designed industrial-scale cold-flow boiler for iron powder (see Figure 6 for details), cold-flow tests were performed. The fluidization pressures measured for bed heights of 200, 300, and 400 mm were 2.36, 3.16, and 3.96 kPa, respectively. The minimum fluidization velocity was calculated to be 0.25 m/s based on the following formula.

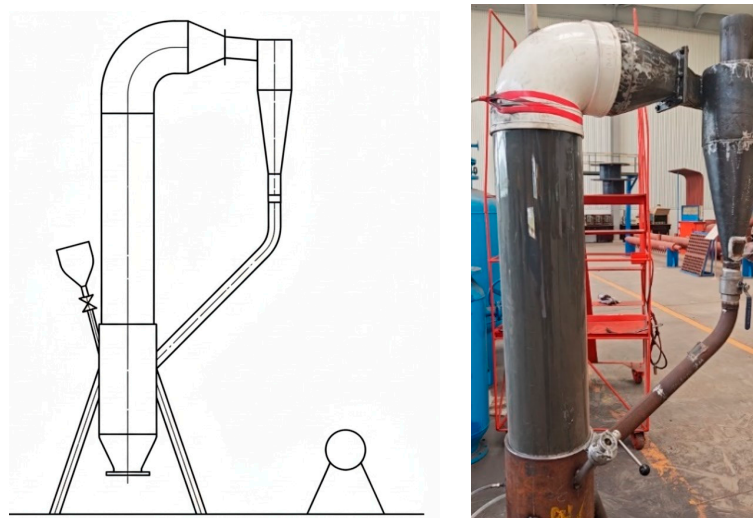


Figure 6. Design and physical diagram of industrial boiler for iron powder cold state experiment.

Where Δp is the bed pressure drop, H is the bed material height, ρ_p and ρ_f are the densities of the iron powder particles and air, respectively, D_1 and D_2 are the bed diameter and distributor plate diameter, respectively, u_{mf} and u_1 are the minimum fluidization velocity and superficial velocity, and ϵ_{ms} and ϵ_{mf} are the particle space occupancy and voidage, respectively.

$$\Delta p = (\rho_p(1 - \epsilon_{mf}) + \rho_f \epsilon_{mf})gH$$

$$u_{mf} = D_1^2 / (n \cdot \epsilon_{mf} D_2^2) \cdot u_1, \quad \epsilon_{ms} = 1 - \epsilon_{mf}$$

In summary, recent studies utilizing representative configurations—Bunsen burners, cyclone combustors, fluidized beds, and rocket nozzles—have systematically elucidated key coupling mechanisms in iron powder combustor design: ① geometric and fuel-feeding parameters determine ignition thresholds and burnout efficiency by regulating particle residence time, recirculation intensity, and oxygen distribution; ② The coupling of particle size and reaction, along with oxidative swelling effects, are the primary drivers of micro-explosion, agglomeration, and deposition; ③ wall thermal boundary conditions and gas thermophysical properties directly influence nanoparticle re-condensation (dominated by thermophoresis/diffusiophoresis) and NO_x formation; ④ the cyclic combustion-reduction process necessitates combustors with controlled temperature gradients and mechanical intervention capabilities to suppress defluidization and sintering. These findings collectively point toward an optimization pathway for industrial scale-up: constructing an internal coupled field within the reactor integrating “controlled oxygen gradient, intensified recirculation, and rapid quenching,” while implementing dynamic feedback regulation via online particle size and temperature monitoring. This establishes the design framework and experimental basis for deploying iron-based fuels in next-generation high-efficiency, low-emission, recyclable thermal energy systems.

3. Iron Cell

Since the 20th century, iron-based electrochemical energy storage has evolved along two parallel technological pathways: liquid and solid electrolyte systems. Liquid electrolyte systems, characterized by low cost and potential for high energy density, have long dominated fundamental research and early-stage demonstrations. In contrast, solid electrolyte systems leverage the ion selectivity and structural integrity of high-temperature ceramic membranes to overcome limitations in cycle life and safety. Over the past decade,

research has further expanded the functional scope of iron-air batteries beyond mere energy storage to include simultaneous power generation, electrocoagulation of pollutants, and resource recovery. This progression positions iron batteries as a critical metallic energy carrier integrating triple values in energy, environmental remediation, and resource cycling. Figure 7 shows the landscape of iron battery research.

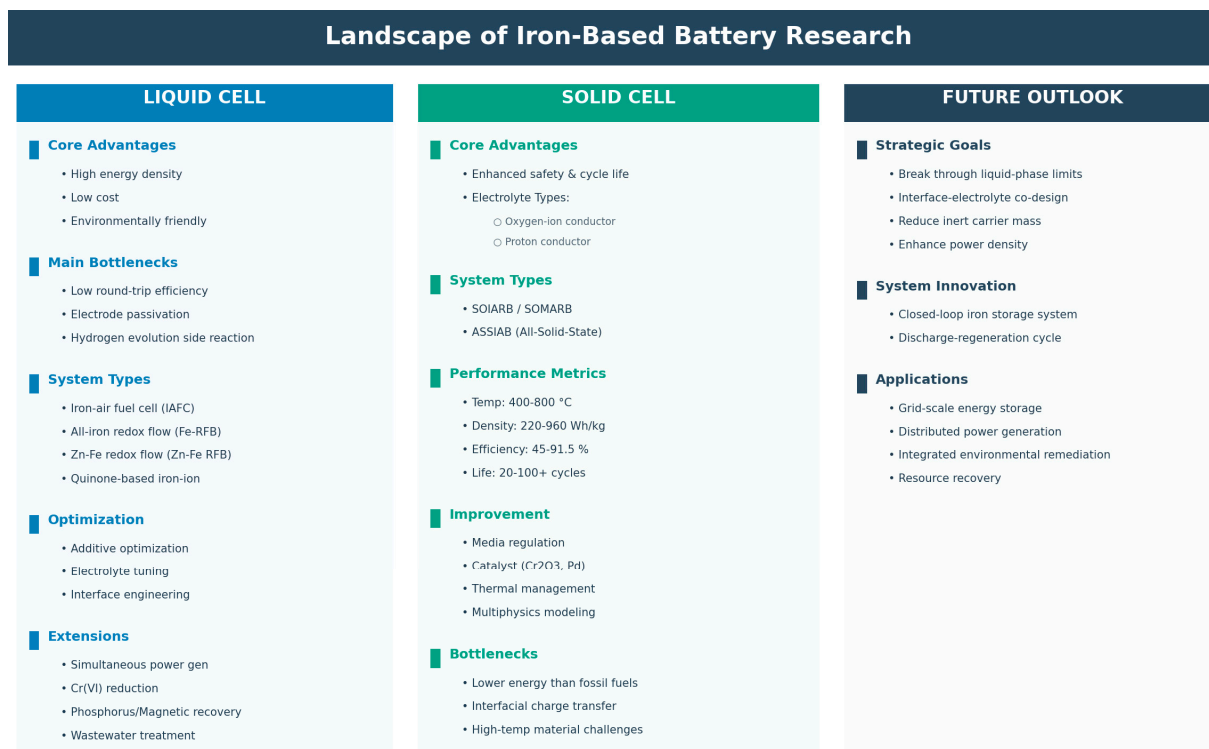


Figure 7. Framework diagram of iron battery research.

3.1. Liquid Cell

Research on liquid iron-air batteries began in the 1970s. In the early years of that decade, Matsushita Electric developed a secondary battery with an energy density of 70 Wh/kg. Subsequently, in 1975, Siemens AG also developed an iron-air secondary battery. This work attracted interest from both the United States and European governments, which subsequently introduced relevant policies to promote research on iron-based batteries [58]. Details of the timeline can be seen in Figure 8.

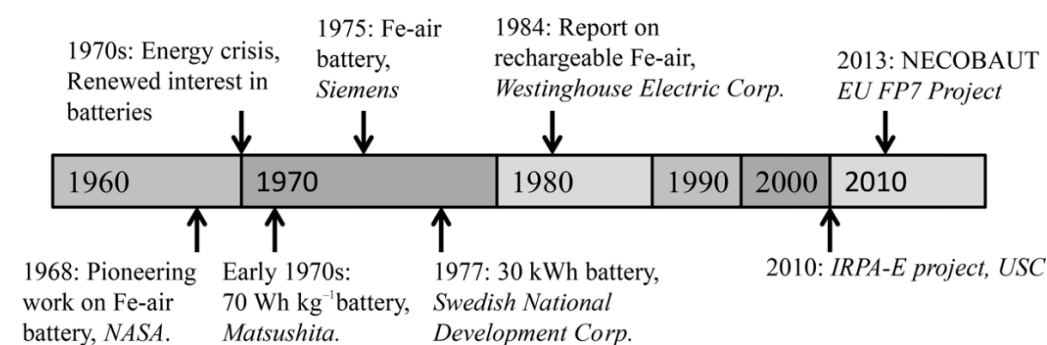


Figure 8. The main development timeline of iron-air batteries in history [58].

In recent years, addressing the contradiction between the “high energy density–low cost” advantages and the “electrode passivation–low energy efficiency–hydrogen evolution”

bottlenecks of iron-air (liquid) batteries, researchers worldwide have conducted systematic explorations from dimensions such as mediator regulation, interface construction, electrolyte formulation, and morphology–chemistry coupling models.

Research on iron-based electrochemical cells is advancing through multi-faceted approaches to overcome persistent challenges including electrode passivation, parasitic hydrogen evolution, and low round-trip efficiency.

Gao et al. [59] systematically outlined these limitations in conventional iron-air batteries and proposed a redox-mediated iron-air fuel cell (RM-IAFC) architecture as a pathway toward flexible recharging and system scalability. Building on the pursuit of performance enhancement, Hang et al. [60] demonstrated that strategic electrolyte additives like LiOH can improve cycling performance, while K₂S effectively suppresses hydrogen evolution. The critical impact of operational parameters was further highlighted by Weinrich et al. [61], who established that the preset charge capacity is a primary determinant of discharge performance. A significant leap in cell design was achieved by Wei et al. [62], who developed an innovative “all-iron” alkaline battery leveraging coordination chemistry; this system realized an ultra-low active material cost of 22 USD kWh^{−1} and maintained high energy efficiency ($\geq 76\%$ after 150 cycles), confirming the feasibility of synergistic low-cost and long-life storage. Concurrently, Fang et al. [63] tackled the passivation problem at its root via sophisticated electrode engineering, creating a nano-iron core confined by a pyrolyzed carbon-nitrogen shell (NanoFe@CN) that enabled a neutral iron-air battery to retain over 90% capacity after 180 cycles. Finally, Song et al. [64] provided a fundamental mechanistic framework, revealing that the Fe(II) electro-oxidation rate is governed by morphochemistry and that the distribution of active core species (FeCO₃, Fe(OH)₂, Fe(CO₃)₂^{2−}) is controlled by factors like pH and carbonate concentration, thus offering predictive insights for optimizing iron-based fuel cell output. Figure 9 reveals the research framework on iron-based electrochemical cells.

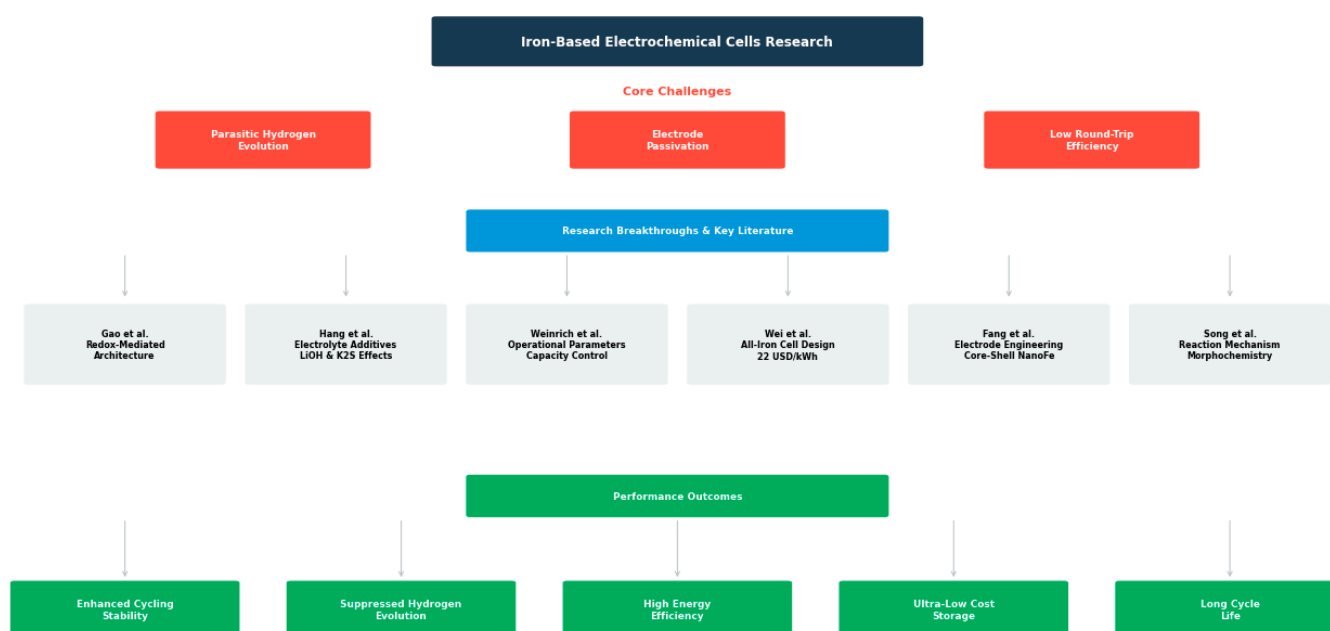


Figure 9. Research framework on iron-based electrochemical cells.

Iron-air fuel cells (IAFCs) represent an emerging platform that transcends the conventional role of batteries. By leveraging the Fe(II)/Fe(III) redox couple, these systems uniquely integrate electrical power output with environmental remediation and resource recovery, effectively functioning as “open reactors.” The underlying principle involves the synergistic

coupling of anodic iron dissolution (providing electrons and Fe^{2+} ions) and the cathodic oxygen reduction reaction (ORR). This process creates a chemical potential field where target pollutants can be reduced, immobilized, and recovered as valuable solid phases, thereby internalizing remediation costs and generating added value alongside electricity.

Research by Kim et al. [65] demonstrated this dual functionality, using an IAFC for electrocoagulation to recover magnetic iron hydroxides while generating a power density of 0.4343 mW/cm^2 . Building on system optimization, Lai et al. [66] identified key operational parameters (e.g., electrolyte conductivity, pH) and highlighted the significant potential of IAFCs for phosphate recovery and energy generation. The efficacy for treating heavy metals was confirmed by Maitlo et al. [67], who found IAFCs to be among the most effective methods for Cr(VI) removal, and by Liu et al. [68], who achieved simultaneous Cr(VI) reduction to Cr(III) and a high power density of 2.88 W m^{-2} , with Cr(III) stabilized via coprecipitation with Fe(III) (hydr)oxides.

Expanding the application scope, An et al. [69] integrated an iron anode into a constructed wetland-microbial fuel cell (CW-MFC-Fe). This innovative system achieved long-term voltage output (650 mV for 200 days) and high removal rates for nitrogen and phosphorus (e.g., 96.0% TN), driven by Fe(0)/Fe(III) cycling and microbial community succession. Most notably, Wang et al. [70] demonstrated the direct recovery of phosphorus as vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) in a sequential batch IAFC, achieving a 97.6% phosphorus removal rate with concurrent power generation, confirming the feasibility of a self-driven, resource-recovering paradigm even with partial anode passivation.

Collectively, these studies validate IAFCs as a transformative technology for achieving the triple synergy of power output, impurity removal, and functional material precipitation, offering sustainable solutions for wastewater treatment and resource recovery in energy-limited settings. Use of iron-air fuel cells as multi-functional reactors is shown in Figure 10.

Iron-based batteries are emerging as promising candidates for grid-scale energy storage, leveraging iron's abundance, low cost, and environmental friendliness. Research focuses on overcoming key challenges like low round-trip efficiency, limited cycle life, and hydrogen evolution through innovative approaches across different battery architectures.

Flow batteries represent a major direction, with the all-iron flow battery (Fe-RFB) advancing due to its simplified "single metal-coordination chemistry" [71]. Key improvements target the electrolyte (e.g., citrate ligands for $\text{Fe}^{2+}/\text{Fe}^{3+}$ regulation and HER suppression) [72], electrodes (carbon-based modifications) [71], and separators. The zinc-iron flow battery (Zn-Fe RFB), utilizing dual aqueous reactions of Zn^{2+}/Zn and $\text{Fe}^{2+}/\text{Fe}^{3+}$, has driven costs below $\$150/\text{kWh}$ and achieved over 10,000 cycles, with ongoing development in pH-decoupled cells and stack design for gigawatt-hour scale integration with renewables [73]. For iron-air batteries, recognized for their potential disruptiveness, the main hurdles are ~50% round-trip efficiency and sub-2000 cycle life [74]. Strategies to boost efficiency to 80% and extend life beyond 5000 cycles include electrode nano-structuring, trifunctional catalysts, and hybrid electrolytes [74].

Innovative system designs are overcoming fundamental kinetic limitations. One approach replaces the metallic iron anode with organic quinones (e.g., 9,10-anthraquinone), which coordinate with Fe^{2+} , drastically reducing polarization and enabling an all-quinone iron-ion battery with significantly improved energy efficiency [75]. Another explores non-aqueous systems using $\text{Fe}||\text{Prussian blue analogue}$ or $\text{Fe}||\text{LiFePO}_4$ configurations, confirming reversible iron deposition/stripping and offering a new "all-iron" route for safe, inexpensive stationary storage [76]. Electrolyte engineering remains crucial, with strategies like operating at elevated temperature combined with coordination ligands proven to reduce viscosity, lower resistance, enhance power density, and extend cycle life

by 2.3 times, providing direct design principles for system optimization [77]. Figure 11 shows the advancing iron-based battery technologies.

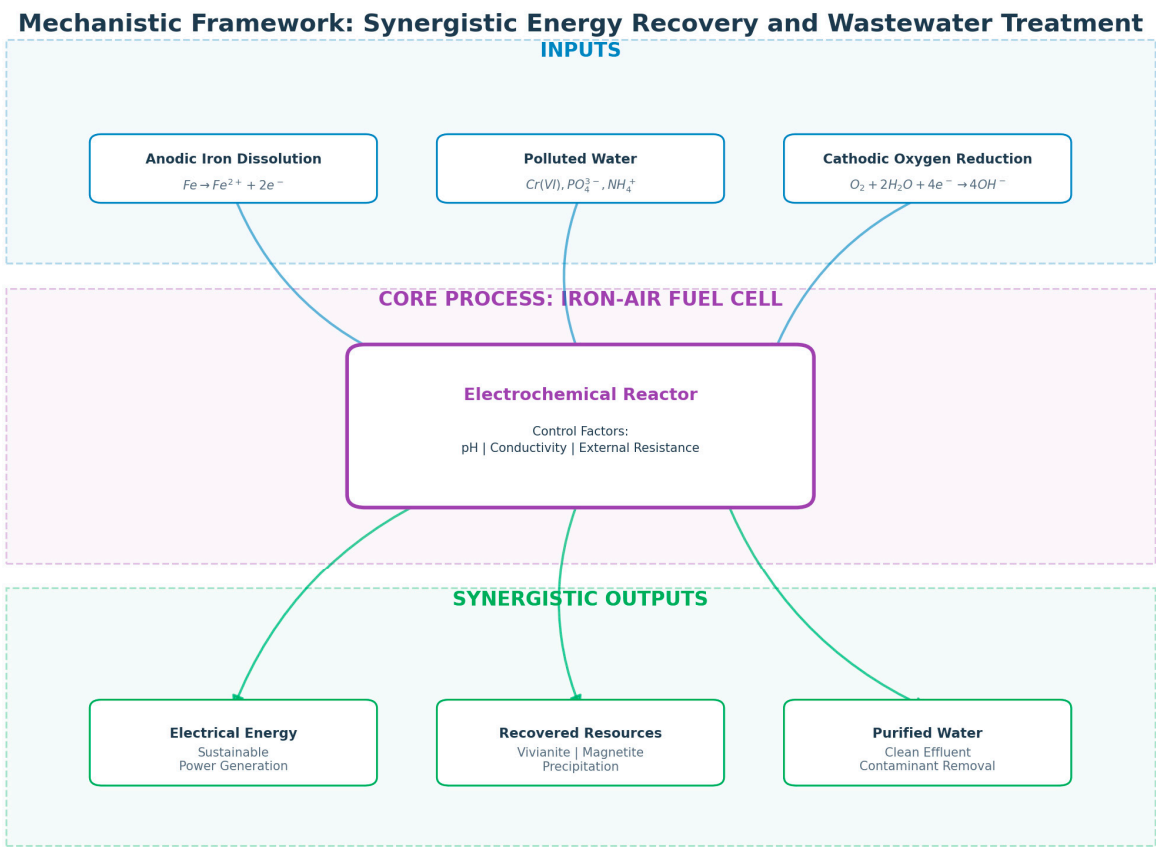


Figure 10. Iron-air fuel cells as multi-functional reactors.

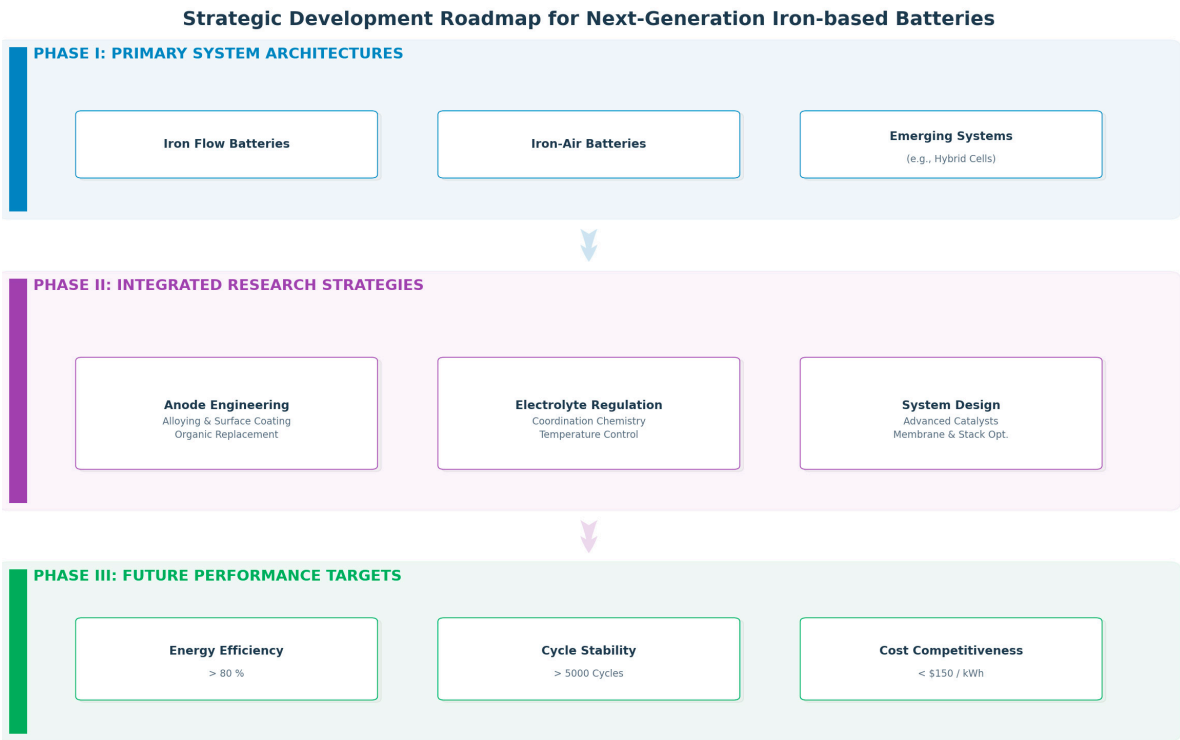


Figure 11. Advancing iron-based battery technologies.

In summary, liquid iron-air and iron-flow battery systems, leveraging their “abundance–cost–multivalency” advantages, have achieved validation in principle and engineering for applications such as combined energy storage and pollution control, and long-duration grid load leveling. Their limitations have also become apparent: electrolyte crossover, parasitic hydrogen evolution reactions, and deposition/stripping polarization result in a round-trip energy efficiency of less than 76%, while the system’s volumetric energy density is constrained by the solubility ceiling.

3.2. Solid Cell

As liquid iron-based electrochemical energy storage systems approach their solubility and mass transfer limits, solid-state electrolytes are envisioned to employ a “lattice anchoring–interfacial confinement” strategy to completely eliminate solvation losses and ion crossover, thereby unlocking new potential for higher energy density and longer cycle life. Consequently, global research is shifting focus towards high-temperature all-solid-state iron-air architectures. These systems utilize oxygen-ion or proton-conducting ceramics to confine the multi-valent Fe/FeOx redox reactions on either side of a dense electrolyte, replacing “solid–liquid” interfaces with “solid–solid” interfaces and integrating reaction and transport processes. Although the system-level energy density of these solid-state systems still lags by orders of magnitude compared to conventional hydrocarbon fuels, and their power density is constrained by interfacial charge transfer and volume expansion stress, the solid-state pathway demonstrates irreplaceable advantages in intrinsic safety, long-term durability, and environmental robustness. This transition represents a logical progression and a necessary paradigm shift for iron-based energy storage, moving from the “liquid-phase paradigm” towards a “high-temperature all-solid-state era.”

Solid-state iron-based batteries represent an emerging technology for large-scale energy storage, leveraging unique mechanisms to overcome traditional limitations. The Solid Oxide Metal Air Redox Battery (SOMARB) enables direct reduction of gaseous oxygen molecules, effectively bypassing the formation of passivating oxide layers that typically hinder mass transfer on oxygen electrodes, thereby significantly enhancing both reaction efficiency and system stability.

Complementing this approach, Wang et al. [78] analyzed All-Solid-State Iron-Air Batteries (ASSIABs), highlighting their ability to circumvent adverse effects associated with high-temperature molten salts or hydrogen/steam environments. While performance requires further improvement, their simplified and safe battery structure positions them as promising candidates for grid-scale storage applications.

Zhang et al. [79] systematically compared SOMARB technology with traditional metal-air batteries, focusing on material design strategies for both Energy Storage Units (ESU) and Reversible Solid Oxide Cells (RSOC). Their review documented advances in enhancing iron-based ESU redox activity and intermediate-temperature RSOC performance through combined experimental and computational approaches, while also outlining remaining challenges toward scalable implementation.

Solid-state iron-air batteries represent a promising high-temperature energy storage technology, with recent research focusing on electrolyte optimization, structural design, and operational stability. Tronico et al. [80,81] demonstrated that LSGM-based electrolytes enable stable cycling at 500–800 °C, achieving energy densities up to 0.46 Wh·g^{−1} with 80% Faradaic efficiency over 100 cycles, while effectively isolating the system from environmental fluctuations. This contrasts with CGO electrolytes, which suffer from self-discharge due to parasitic electronic conduction.

Structural innovations include Wilke’s finite element model [82], which revealed that layered iron foam architectures withstand the 74% volume expansion during oxidation bet-

ter than dendritic structures, explaining their superior cycling longevity. Drenckhahn [83] validated this technology at kilowatt scale using planar SOFC/SOEC configurations, achieving power densities exceeding 250 mW/cm² for 2 h durations. Table 4 shows the key parameters of high-temperature all solid-state batteries in recent years.

Table 4. Key parameters of high-temperature all solid-state batteries in recent years.

Cell Sorts	Electrolyte	Temperature Range	Energy Efficiency	Operating Cycle	Current Density/mA·cm ⁻²	Specific Energy/Wh·kg ⁻¹
SOMARB	YSZ	800 °C	91.5%	20 cycles	50	348
	ScSZ	550 °C	62.9%	12.5 h	10	625
	LSGM	500 °C	90%	30 cycles	5	—
	LSGM	450 °C	80%	50 cycles	0.04	500
	ScSZ	550 °C	45%	2.5 h	10	601.9
	LSGM	400 °C	82.9%	—	—	600
ASSIAB	LSGM	800 °C	—	—	0.4 A·g ⁻¹	220
	LSGM	650 °C	54%	100 cycles	1.4 A·g ⁻¹	458
RFB	PEMFC	600 °C	—	—	—	209.4

Electrolyte composition critically affects durability. Cui [84] and Fang's team [85] found that replacing LiCl with sulfate/carbonate electrolytes suppresses nickel electrode corrosion, extending cycle life to over 850 cycles with 88.6% coulombic efficiency. Operating temperature optimization by Inoishi [86] revealed that 773 K maximizes discharge potential (1.07 V) by preventing anode aggregation while maintaining >80% round-trip efficiency over 30 cycles. Figure 12 shows the solid-state iron-air battery development.

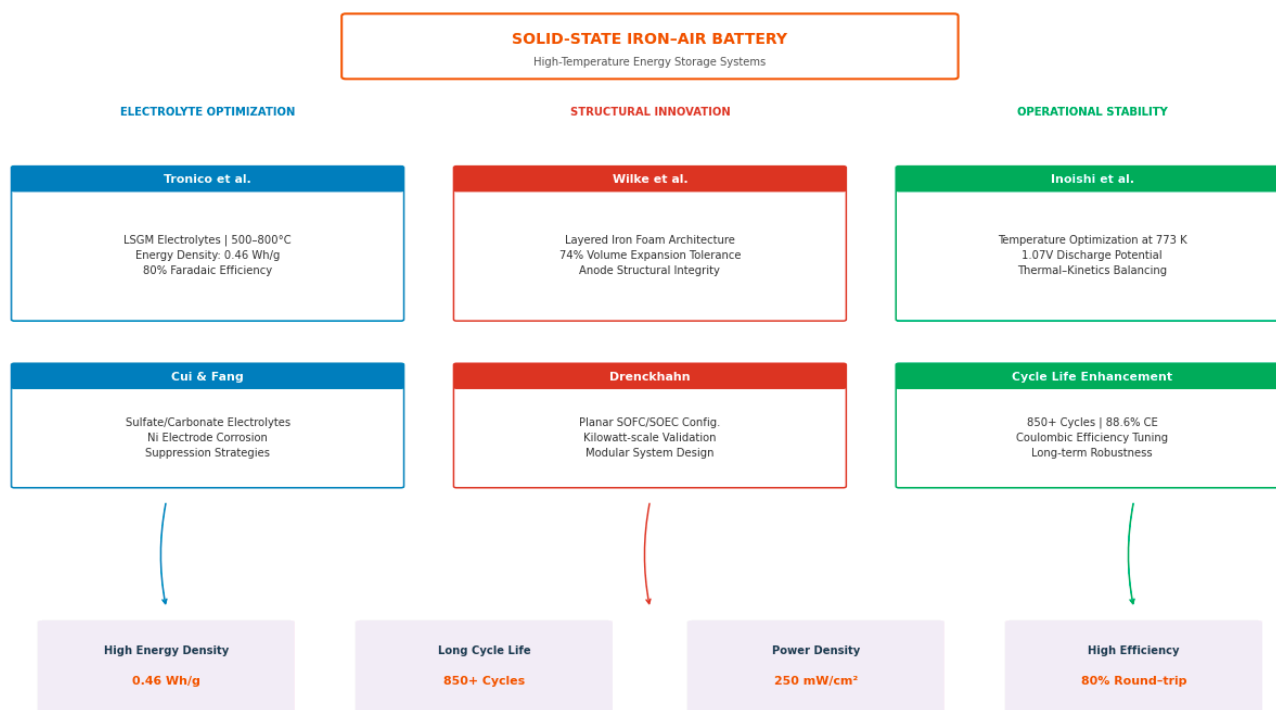


Figure 12. Solid-state iron-air battery development.

Recent research on solid oxide iron-air batteries has yielded significant improvements in thermal management, catalytic enhancement, and operational efficiency through sophisticated material engineering and system optimization.

Jin's team [87,88] conducted comprehensive multiphysics analyses revealing critical operational insights. Their thermal management study demonstrated that discharge heat

substantially exceeds charging requirements, with air utilization rate and inlet temperature identified as key thermal control variables. Operation at 1500 A/m² enabled thermal self-sustaining, though with reduced electrical efficiency. Further investigation at 550 °C identified charging performance as primarily limited by Fe₃O₄ reduction kinetics, with charging current density, depth of discharge, and reduction rate having the most significant impact on overall performance.

Catalyst development has proven crucial for enhancing redox kinetics. Kim et al. [89,90] achieved remarkable stability improvements through strategic doping, with 3 wt% Cr₂O₃ and 3 wt% PrBaMn₂O₅ enabling over 50 stable cycles and discharge capacity exceeding 770 mA·h·gFe⁻¹ at 623 K. Composite iron with Ce_{0.6}Mn_{0.3}Fe_{0.1}O₂ (CMF) further increased oxidation rate constants by an order of magnitude, achieving 80% initial oxidation and stable 600 mAh·gFe⁻¹ capacity over 20 cycles at 673 K.

Advanced material strategies have pushed efficiency boundaries. Tang et al. [91] utilized proton conductor BZC4YYb with an iridium catalyst to achieve 82.9% round-trip efficiency and 601.9 Wh·kg⁻¹ energy density at 550 °C with stable 250 h operation. Zhang’s team [92] incorporated palladium nanoparticles, enabling 960.3 Wh·kg⁻¹-Fe specific energy at 500 °C with maintained 62.9% average efficiency over 25 cycles, demonstrating the potential for high-energy density storage. Advancements in Solid Oxide Iron-Air Batteries is shown in Figure 13.

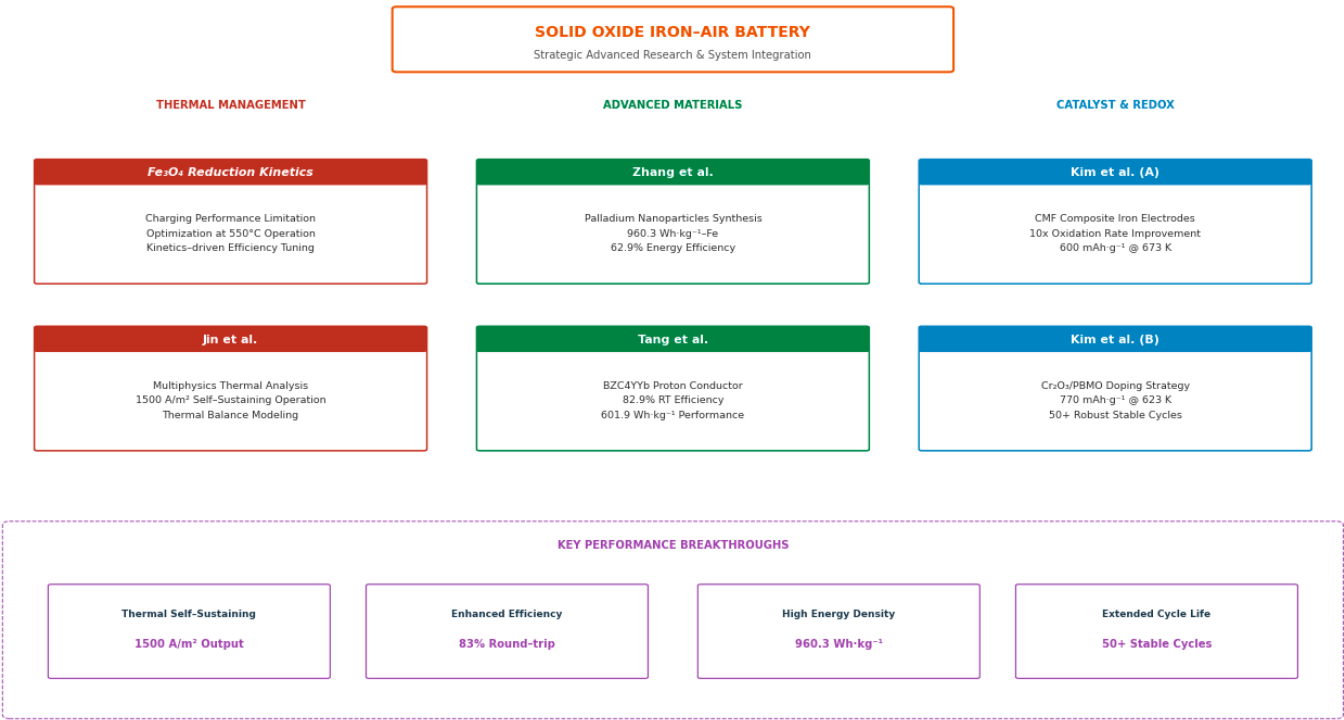


Figure 13. Advancements in Solid Oxide Iron-Air Batteries.

Compared to liquid electrolyte systems, solid-state iron-air batteries offer significant advantages in terms of safety and cycle life. However, their system-level energy density remains approximately “an order of magnitude lower” than that of conventional fossil fuels [93]. This performance level currently only meets the minimum range requirements for small passenger vehicles. For applications with simultaneous demands for high power density and high energy density—such as heavy-duty trucks, engineering equipment, military vehicles, locomotives, and ships—there remains a significant performance gap, rendering the technology currently unfeasible for these sectors.

Distinguished from conventional iron flow batteries, the “battery-as-factory” concept functions as an electrochemical refinery producing solid iron fuel, achieving superior energy density ($\sim 40 \text{ GJ/m}^3$) while eliminating membrane-related degradation. Although iron has a higher hydrogen evolution (HER) tendency than zinc, targeted batteries effectively suppresses side reactions; compared to irreversible aluminum or dendrite-prone zinc systems, this iron-based pathway offers superior chemical reversibility and zero self-discharge, ensuring higher system-level efficiency and stability for long-duration storage [94].

Currently, iron-air batteries have developed into a multi-tiered technological spectrum encompassing “aqueous and solid-state electrolyte systems”. Room-temperature liquid-phase routes offer process compatibility but are hampered by electrode passivation and parasitic hydrogen evolution reactions. High-temperature solid-state routes can achieve a balance between round-trip efficiency and cycle life, yet they still face dual constraints of limited single-cell energy density and interfacial mechanical failure. Although the iron anode leverages the high energy density of the metal and utilizes oxygen from the air—theoretically enabling significant improvements in energy and power density—the sluggish kinetics of the cathode oxygen reduction reaction at low temperatures forces the system to rely on expensive catalysts, high-surface-area supports, and inert electrolytes. This ultimately results in persistently low power density.

3.3. Levelized Cost of Iron Cell

3.3.1. Thermodynamic Analysis: Entropy Increase and Energy Penalty

The iron fuel cycle involves a sequence of energy conversions: Renewable Electricity $\rightarrow$ Hydrogen $\rightarrow$ Reduced Iron $\rightarrow$ Thermal Energy. According to the Second Law of Thermodynamics, each step is accompanied by an entropy increase ($\Delta S_{total} > 0$), which dictates the minimum energy input required.

Electrolysis Step: The conversion of electricity to chemical potential in H_2 involves ohmic heating and overpotentials.

Reduction Step ($Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$): This process is endothermic. The entropy increase is driven by the phase change and the high-temperature requirements (typically $> 700^\circ\text{C}$). The energy consumption in the reduction process is directly proportional to the “energy quality” lost.

The “Entropy Debt”: To close the cycle, the energy required to reduce iron ore is significantly higher than the energy recovered during combustion. The Round-Trip Efficiency (RTE) is estimated as

$$\eta_{RTE} = \eta_{electrolysis} \times \eta_{reduction} \times \eta_{combustion} \approx 0.75 \times 0.80 \times 0.90 \approx 54\%$$

This 46% energy loss represents the thermodynamic “tax” paid to maintain a carbon-free, transportable solid fuel.

3.3.2. Simplified LCOE Model for Iron Fuel

To quantify the economic feasibility, we define the Levelized Cost of Energy ($LCOE_{iron}$) as the cost per unit of thermal energy delivered (USD/kWh_{th}).

A. Cost Equation

$$LCOE_{iron} = \frac{C_{elec}}{\eta_{sys}} + \frac{CAPEX_{ann} + OPEX_{fix}}{CF \cdot 8760 \cdot P_{rated}}$$

where

C_{elec} : Price of renewable electricity (USD/kWh).

η_{sys} : System-wide efficiency (Electrolysis $\times$ Reduction ≈ 0.60).

$CAPEX_{ann}$: Annualized capital cost of electrolyzers and fluidized bed reactors.

CF: Capacity factor of the renewable energy source.

B. Threshold Calculation

Assuming a standard CAPEX/OPEX for green hydrogen infrastructure, the energy cost (C_{elec}/η_{sys}) typically accounts for 70–80% of the total iron fuel cost, which can be seen in Table 5.

Table 5. Relevant parameter of threshold calculation.

Parameter	Value (Conservative)	Value (Optimistic)
Electricity Price (C_{elec})	\$0.06/kWh	\$0.02/kWh
System Efficiency (η_{sys})	50%	65%
Levelized Capital Cost	\$0.02/kWh _{th}	\$0.01/kWh _{th}
Total $LCOE_{iron}$	0.14/kWh _{th}	0.04/kWh _{th}

3.3.3. Economic Feasibility Thresholds

The iron fuel cycle becomes economically viable only when it competes with established energy carriers or carbon-taxed fossil fuels.

The \$0.03/kWh Threshold: If the target is to match the cost of industrial natural gas (approx. \$0.04–0.06 per kWh thermal), the input electricity price must be \$0.03/kWh. At this price point, the fuel cost component drops to ~0.046/kWh_{th} (assuming 65% efficiency), making it competitive for heavy industry.

Sensitivity to Renewable Costs: Because the reduction process is energy-intensive (~3.5 MWh per tonne of iron), a \$0.01 fluctuation in electricity price results in a ~\$35/tonne shift in iron fuel production costs.

The Carbon Parity Point: At an electricity price of \$0.05/kWh, iron fuel requires a carbon price of approximately \$150–\$200/tonne CO₂ to reach parity with coal-fired thermal plants.

3.3.4. Conclusion of Analysis

The techno-economic viability of the iron fuel cycle is strictly governed by the “entropy–cost correlation.” High entropy production in the reduction phase necessitates extremely low-cost renewable inputs to offset efficiency losses.

Feasibility Conclusion: For iron fuel to serve as a global energy commodity, reduction facilities must be co-located with “ultra-low-cost” renewable zones (e.g., Australia, Chile, or Middle East) where cost <\$0.03/kWh is achievable. Without this, the energy penalty of the iron–hydrogen–iron cycle remains too high for market penetration.

4. Conclusions and Future Directions

4.1. Conclusions

This article addresses the core question of “whether iron can inaugurate a new era of zero-carbon energy,” systematically reviewing the research progress of iron as a metallic energy carrier along both combustion and electrochemical pathways, and draws the following conclusions:

(1) Combustion Pathway:

- ① At the single-particle scale, a five-stage mechanistic framework of “heating–melting–intense combustion–cooling–re-ignition” has been established, clarifying that gas-phase FeO(g) reactions contribute $\geq 18\%$ to the total heat release and proposing $Da \approx 1.2$ as the criterion for the diffusion–kinetics transition.
- ② At the particle-cloud scale, the macroscopic scaling laws of $t_e \propto d^2$ and $S_1 \propto d^{-1}$ have been elucidated, revealing the mechanisms of micro-explosion, agglomer-

ation, and nanoparticle generation governed by the coupling of particle size, porosity, and oxide layer thickness.

- ③ At the combustor level, it has been demonstrated that a coupled field of “controlled oxygen gradient, intensified recirculation, and rapid quenching” can simultaneously achieve $\geq 94\%$ burnout efficiency with low NO_x and nPM emissions, providing design guidelines for the scale-up of MW-level fluidized-bed and cyclone combustors.
- (2) Electrochemical Pathway:
- ① Liquid Systems: Alkaline/neutral Fe-air batteries and Fe-RFBs have achieved coulombic efficiencies of 76–99%, cycle lives of 150–10,000 cycles, and demonstrated that the synergistic “elevated temperature + coordination” strategy suppresses hydrogen evolution and dendrites, reducing energy costs to <150 USD kWh^{−1}.
 - ② Solid Systems: Batteries utilizing 800 °C-class LSGM oxygen-ion conductors have achieved 0.22–0.46 Wh g^{−1}, 80% round-trip efficiency, and stable operation for 100–250 h, although their volumetric energy density remains an order of magnitude lower than gasoline.
 - ③ Functional Extension: Iron-Air Fuel Cells (IAFCs) have simultaneously achieved Cr(VI), phosphate, and organic pollutant removal alongside power generation at 2.88 W m^{−2}, validating the feasibility of the triple synergy of “energy storage–pollution control–resource recovery.”
- (3) Common Bottlenecks:
- ① Combustion Side: High-temperature reduction–oxidation cycles lead to particle agglomeration, defluidization, and sintering, necessitating the development of online regeneration technologies coupling controlled atmospheres with mechanical intervention.
 - ② Battery Side: Liquid-phase systems are limited by Fe(OH)₂/Fe₃O₄ passivation films and hydrogen evolution side reactions, while solid-state systems are constrained by Fe/FeOx volume expansion, interfacial delamination, and the insufficient low-temperature conductivity of oxygen-ion conductors.
 - ③ System Side: The closed-loop iron–iron oxide cycle has not yet undergone economic validation, and there is a lack of integrated GW-scale demonstrations coupling “powder production–combustion–reduction” with renewable electricity.

In conclusion, the combustion-based and electrochemical iron systems are not competing alternatives but rather complementary and sequentially integrated pathways within a unified zero-carbon energy infrastructure. The combustion pathway is uniquely optimized for heavy industrial decarbonization, providing high-grade thermal energy and high power density required for retrofitting existing thermal power plants and maritime shipping. Conversely, the electrochemical pathway (both liquid and solid-state) serves the needs of grid-scale long-duration storage and decentralized power generation, offering high round-trip efficiency and environmental synergies such as pollutant removal. These two modalities are sequentially linked by a shared upstream reduction infrastructure—where renewable energy ‘charges’ iron through hydrogen-based or electrolytic reduction—and a unified downstream logistics network for iron oxide recovery. By offering a dual-mode discharge capability (heat vs. electricity) from a single, stable carrier, iron enables a flexible, multi-modal energy economy where the choice between combustion and electrochemical conversion is determined by the specific thermodynamic demands of the end-use

application rather than carrier limitations. Table 6 shows the differences of iron-based energy pathways.

Table 6. System-Level Comparison of Iron-Based Energy Pathways [37,38,78,79].

Feature	Combustion Pathway	Liquid Electrochemical Pathway	Solid Electrochemical Pathway
Core Technology	MW-scale Fluidized-bed/Cyclone Combustors	Alkaline/Neutral Fe-Air & Fe-Redox Flow Batteries	800 °C-class LSGM Oxygen-Ion Conductor Batteries
Energy Output	High-grade Thermal Energy (>1500°C) → Steam/Electricity	Direct Electrical Power (Low-cost discharge)	High-efficiency Direct Electrical Power
Performance Metrics	≥94% Burnout efficiency; Low NOx and nPM	76–99% Coulombic efficiency; 150–10,000 cycles	0.22–0.46 Wh g ^{−1} ; 80% Round-trip efficiency (RTE)
Byproduct Management	Dry Iron Oxide (Fe ₂ O ₃) particles via cyclone capture	Iron Oxide sludge; multi-synergy for pollution control (IAFCs)	Solid-state Fe/FeO _x transition; Risk of interfacial delamination
Primary Use Cases	Heavy Industry Heat, Retrofitted Power Plants, Maritime Shipping	Grid-scale Long-duration Storage (LDES), Distributed Power	High-efficiency Stationary Storage, Specialized Power Units
Critical Bottlenecks	Particle sintering, agglomeration, and defluidization during redox cycles	Passivation films (Fe(OH) ₂) and Hydrogen Evolution Reaction (HER)	Volume expansion and low-temperature ionic conductivity limits

4.2. Strategic Research Needs and Future Outlook

While the foundational science of iron-based energy is established, transitioning from proof-of-concept to industrial reality requires addressing significant technical and economic uncertainties. The following conceptual directions represent the priority areas for future research:

(1) Advanced Diagnostics and Combustion Scaling: There is a critical need for multi-scale, full-cycle investigative frameworks to bridge the gap between single-particle kinetics and industrial burner performance. Future research should prioritize the integration of in situ diagnostics (such as XRD/CT) with high-fidelity simulations to capture the stochastic nature of 3D agglomeration. Furthermore, while the potential for low-energy iron regeneration (< 700 °C) and ammonia co-combustion is promising, the uncertainty regarding long-term reactor stability and the complex pollutant interactions in 1–10 MWth demonstrations remains a primary hurdle. Research must evolve from reporting efficiency to establishing dynamic models that predict defluidization risks under varied industrial loads.

(2) Interfacial Engineering and Material Stability in Electrochemical System: The future of iron-based electrochemical storage lies in overcoming the fundamental limitations of the iron-electrolyte/ion interface.

Liquid Systems: Conceptual focus should shift toward understanding the dynamic equilibrium of Fe(II)/Fe(III) coordination. While high-performance interfaces (e.g., 3D porous carbon) are desirable benchmarks, their long-term durability under aggressive alkaline conditions remains an open question.

Solid Systems: Reducing operating temperatures to the 500–550 °C range via mixed conductors is a strategic necessity to prevent sintering; however, the reliability of bilayer membranes and composite anodes over thousands of thermal cycles is not yet validated.

Emerging Chemistries: Exploring iron-free anodes or coordination chemistry offers a high-reward, albeit high-uncertainty, pathway to eliminate metallic polarization, requiring deeper investigation into the fundamental kinetics of organic–metal ion interactions.

(3) System-Level Integration and Economic Uncertainties To move toward a viable metallic energy economy, research must move beyond component-level analysis to comprehensive system modeling.

Energy Hubs: Conceptual “renewable electricity–hydrogen–iron” hubs require rigorous time-series simulations to account for the intermittency of renewables. Achieving com-

petitive storage costs ($\leq 2 \text{ € kWh}^{-1}$) and high round-trip efficiency ($\geq 60\%$) remains a theoretical target that is highly sensitive to future hydrogen prices and carbon tax fluctuations.

Standardization and Infrastructure: Establishing standardized protocols for powder safety, impurity limits, and lifecycle carbon footprints is a foundational requirement for international trade.

Demonstration Risks: The conceptual design of 100 MWe-class combined cycle plants must explicitly address the uncertainties of corrosion-erosion impacts on gas turbine components—a critical bottleneck that currently lacks long-term empirical data.

In summary, iron-based energy is entering a phase where performance, cost, and cyclability must be optimized synergistically. While the technical pathways are becoming clearer, the timeline for commercialization—potentially within the next decade—depends on resolving the significant gaps between laboratory-scale findings and the complex, harsh environments of industrial energy systems. By addressing these conceptual needs, iron has the potential to emerge as a scalable and affordable third major zero-carbon energy carrier, alongside hydrogen and ammonia.

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