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Economic competitiveness and environmental trade-offs of polysulfide–ferrocyanide redox flow batteries

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Abstract

Low-cost redox chemistries offer opportunities for long-duration energy storage, but their economic and environmental competitiveness remains uncertain. Here we integrate experimental electrochemical characterization, techno-economic analysis and life-cycle assessment to evaluate polysulfide–ferrocyanide redox flow batteries (S–Fe RFBs) against all-vanadium benchmarks. At a rated power of 1 MW, S–Fe RFBs achieve modelled levelized costs of storage of €344 and €291 MWh^{-1} for 4 and 8 h durations, respectively, representing reductions of 9.5% and 8.5% relative to vanadium systems. Sensitivity analysis identifies calendar stability and efficient operation at higher current densities as key opportunities for further cost reduction. Reducing calendar degradation to 0.005% day^{-1}, together with improved capacity utilization and reduced polarization, could lower the 4 h storage cost to €285 MWh^{-1}. However, under wind-electricity charging, S–Fe RFBs exhibit 8.5% and 22.0% higher life-cycle global warming impacts than their vanadium counterparts at 4 and 8 h, respectively. These environmental burdens are strongly influenced by component manufacturing, charging electricity and storage duration. Prospective higher-voltage chemistries offer further opportunities for cost reduction, although their economic and environmental benefits remain conditional on achieving the assumed performance. These findings identify priorities for electrochemical development and reveal the trade-offs between economic competitiveness and environmental sustainability in aqueous flow batteries.

Introduction

The rapid expansion of renewable electricity generation is increasing the demand for affordable and sustainable long-duration energy storage.[1,2] Global renewable capacity additions are projected to approach 4,600 GW between 2025 and 2030, nearly doubling those during 2019–2024 (Fig. 1a).[3] This accelerated deployment will increase the temporal mismatch between renewable generation and electricity demand, placing greater pressure on grid flexibility and energy storage infrastructure.[2] Growing renewable penetration has already been accompanied by substantial electricity curtailment in several markets (Fig. 1b), highlighting the need for storage technologies capable of absorbing surplus electricity and delivering it when required.[3,4] However, the economic viability of storage depends not only on initial capital costs but also on energy efficiency, degradation and maintenance over its operating lifetime.[5,6] Similarly, low-cost battery materials do not necessarily translate into low environmental impacts.[7] **Understanding these relationships is essential for developing energy storage technologies that are both economically competitive and environmentally sustainable**.

Aqueous redox flow batteries (RFBs) are promising candidates for stationary energy storage because their

power and energy capacities can be scaled largely independently.[8] All-vanadium RFBs (VRFBs) have achieved commercial deployment, benefiting from established electrochemistry and the use of vanadium species in both electrolytes, which enables capacity recovery through electrolyte rebalancing (Fig. 1c).[9] However, the relatively high cost of vanadium electrolytes increases energy-related capital expenditure, particularly as storage capacity is expanded for longer discharge durations.[10,11] This dependence on costly active materials limits the potential for further cost reduction despite the technological maturity of VRFBs. Alternative aqueous chemistries based on organic molecules, metal ions and sulfur compounds have therefore attracted increasing interest.[8,12,13] Among these, polysulfide–ferrocyanide RFBs (S–Fe RFBs) offer an attractive combination of inexpensive active materials (US$0.50 kg^{-1} for K_2S_2 and US$2.15 kg^{-1} for $K_4Fe(CN)_6{\cdot}3H_2O$),[14,15] high electrolyte solubility (8.8 mol L^{-1} for K_2S in alkaline solution),[16] and aqueous operation (Fig. 1d). Nevertheless, their relatively low cell voltage, sluggish polysulfide reaction kinetics and active-species crossover limit energy efficiency and capacity retention, potentially offsetting the advantages of low material costs.[17,18]

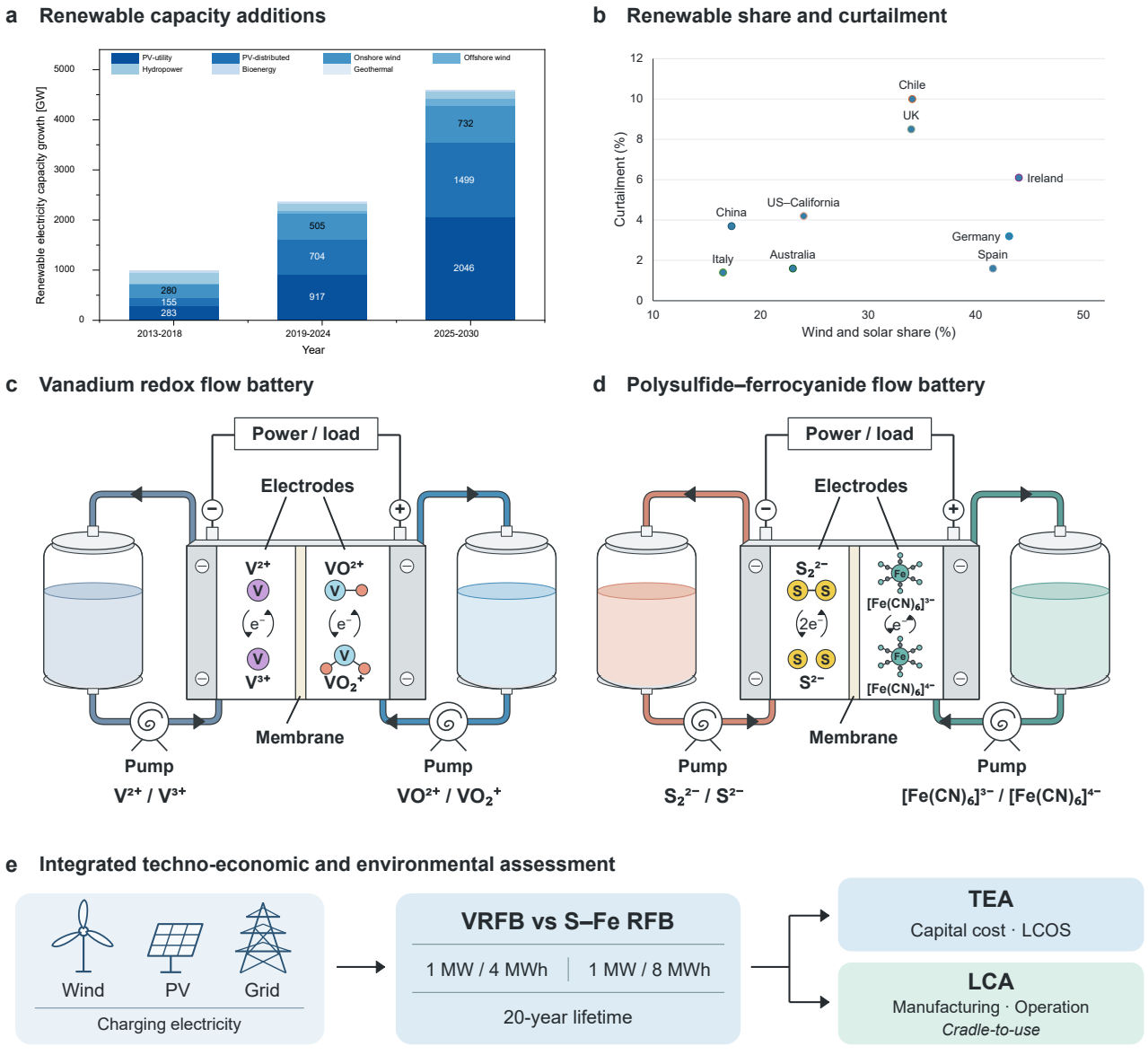


Fig. 1 Renewable energy deployment, redox flow battery chemistries and integrated assessment framework. **a**, Historical and projected global renewable electricity capacity additions by technology. **b**, Relationship between wind and solar electricity shares and renewable electricity curtailment across selected countries and regions. **c**, Schematic of a VRFB, illustrating the vanadium redox couples, electrolyte circulation and cell configuration. d, Schematic of an S–Fe RFB, showing the redox-active species and electrolyte configuration. e, Integrated TEA and LCA framework comparing 1 MW/4 MWh and 1 MW/8 MWh systems under wind, photovoltaic and grid-electricity charging scenarios, with evaluation of storage costs, environmental impacts and key performance sensitivities. a and b are adapted from IEA, Renewables 2025.[3]

Recent advances in catalytic electrodes and ion-selective membranes have improved the electrochemical performance of S–Fe RFBs, particularly reaction kinetics and cycling stability.[19–21] Molecular and relay catalysts offer further approaches to accelerating polysulfide conversion.[22,23] However, the extent to which these improvements translate into economic benefits remains unclear. At the system level, increasing operating current density reduces the electrode area required for a given power output but can increase polarization losses and electricity consumption.[10,11] Likewise, improved electrolyte stability can reduce maintenance and replacement costs, whereas higher cell voltage and greater capacity utilization can lower the material requirements for a given storage capacity.[10,24] These competing effects make it difficult to infer economic competitiveness directly from individual electrochemical metrics. A quantitative framework linking battery performance, system design and lifetime storage costs is therefore needed to identify the most effective directions for technological improvement.[25]

Beyond economic performance, the environmental implications of emerging RFB chemistries remain insufficiently understood. Life-cycle assessments of established VRFB systems have highlighted the contributions of electrolyte production, cell components and operational electricity to environmental burdens.[26,27] Although inexpensive and abundant active materials may reduce resource-related impacts, their potential advantages can be offset by greater material consumption, lower energy efficiency or more frequent component replacement.[28,29] Moreover, the carbon intensity of charging electricity and the duration of energy storage can substantially influence environmental impacts per unit of delivered electricity.[28,29] Consequently, improvements that reduce the levelized cost of storage (LCOS) may not necessarily reduce environmental burdens.[30] Understanding these economic–environmental trade-offs is particularly important for S–Fe RFBs, where material cost advantages coexist with limitations in electrochemical performance.

Here we integrate experimental electrochemical characterization, techno-economic analysis (TEA) and life-cycle assessment (LCA) to evaluate the economic and environmental competitiveness of S–Fe RFBs against established VRFB benchmarks (Fig. 1e). We assess 1 MW systems with storage durations of 4 and 8 h, examining how electrochemical performance, calendar degradation, operating conditions and system design influence lifetime storage costs and environmental impacts. The baseline S–Fe systems achieve lower modelled LCOS than their vanadium counterparts but exhibit higher global warming impacts under wind-electricity charging. Sensitivity analyses identify calendar stability, current density and voltage efficiency as important determinants of storage economics, while prospective higher-voltage scenarios reveal opportunities for further improvement. Together, these findings establish quantitative performance targets for S–Fe RFB development and highlight the need to consider economic and environmental outcomes jointly when evaluating emerging battery chemistries.

Electrochemical performance of a laboratory-scale S–Fe RFB

Although S–Fe RFBs offer considerable potential for low-cost energy storage, their technological development remains at the laboratory scale.[13,17] Establishing reliable electrochemical operation is therefore an important prerequisite for evaluating their economic and environmental potential. Here, we characterized a laboratory-scale S–Fe cell to assess its electrochemical reversibility and cycling stability (Fig. 2). The initial impedance measurement yielded an area-specific resistance (ASR) of~2.0 Ω cm^2 (Fig. 2a). Charge–discharge profiles recorded at different cycling stages maintained similar voltage characteristics with limited changes in polarization (Fig. 2b), suggesting stable electrochemical reaction kinetics under the investigated conditions.

The cell exhibited consistent voltage responses over approximately 400 h of continuous operation (Fig. 2c). Over 1,000 cycles, the coulombic efficiency (CE) remained close to 100%, while the average voltage efficiency (VE) was approximately 81.5%, accompanied by relatively stable discharge capacity (Fig. 2d). Changes in capacity following electrolyte replenishment suggest that variations in the active-species inventory contributed to the observed capacity fluctuations. The measured cell exhibited an open-circuit voltage (OCV) of 0.97 V, with estimated crossover-induced capacity fade and electrolyte decay rates of 0.0018% and 0.0020% per cycle, respectively (Supplementary Table 1). The results demonstrate the stable and reversible operation of the S-Fe RFB at the laboratory scale, providing a solid foundation for further scale-up. However, promising batteries performance does not necessarily translate into economic viability. In practical application, the economic competitiveness of redox flow batteries is influenced by multiple factors, including material cost, stack costs, system efficiency, operation lifetime and maintenance expenses. Therefore, a TEA is essential to evaluate the potential of the S-Fe RFB for large-scale energy storage applications. By integrating experimentally obtained performance parameters with a system-level cost model, the TEA enables a quantitative assessment of energy storage costs and economic feasibility while identifying the key technical and economic factors that may influence future commercialization.

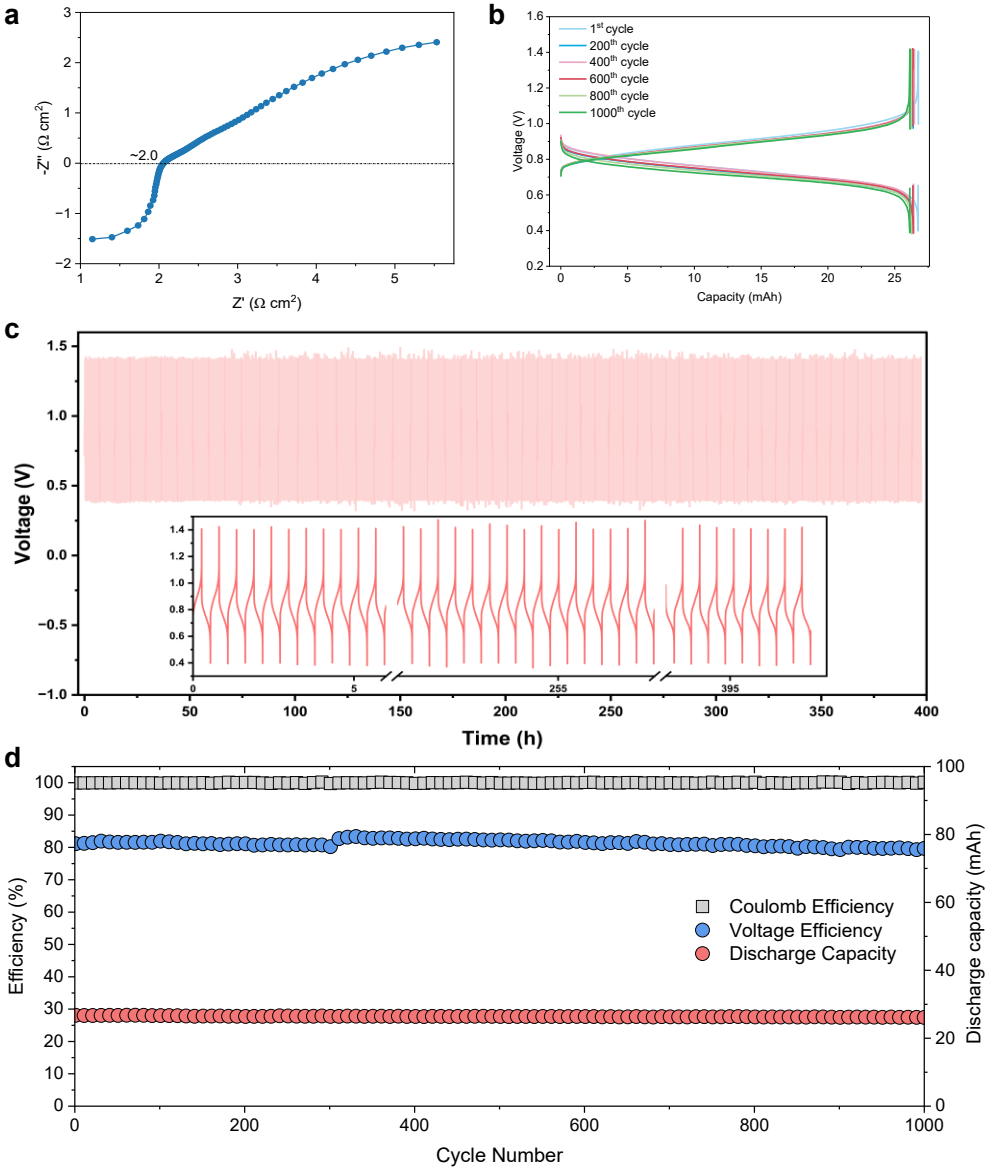


Fig. 2 Electrochemical performance and cycling stability of a laboratory-scale S–Fe RFB. a, Electrochemical impedance response of the cell. **b**, Representative charge–discharge voltage profiles at different cycling stages. **c**, Cell voltage during approximately 400 h of continuous cycling, with the inset showing representative charge–discharge cycles. **d**, CE, VE and discharge capacity over 1,000 cycles, demonstrating the electrochemical reversibility and cycling stability of the laboratory-scale cell.

Techno-economic assessment of S–Fe RFBs

To assess whether the electrochemical performance demonstrated at the laboratory scale could translate into economic competitiveness, **we conducted a prospective TEA combining experimental parameters with system-level engineering and financial assumptions**.[25] We modelled 1 MW S–Fe RFB systems with storage durations of 4 and 8 h, using duration-matched VRFBs as benchmarks (Supplementary Tables 1–4). For the 4 h configuration, the estimated capital cost of the S–Fe system is €349 kWh^{-1}, 20.3% lower than the VRFB benchmark of €438 kWh^{-1} (Fig. 3a and Supplementary Fig. 1). Balance-of-plant (BOP) equipment accounts for the largest share of capital expenditure (38.2%), followed by electrolyte materials (14.7%) and fabrication (8.5%), whereas membranes contribute only 2.0%. This breakdown indicates that inexpensive active materials provide a capital-cost advantage, although auxiliary equipment and system integration remain substantial cost contributors.

The modelled LCOS of the 4 h S–Fe system is €344 MWh^{-1}, compared with €380 MWh^{-1} for the VRFB, representing a 9.5% reduction (Fig. 3b). Extending storage duration to 8 h lowers the S–Fe capital cost to €221 kWh^{-1} and LCOS to €291 MWh^{-1}, compared with €303 kWh^{-1} and €318 MWh^{-1} for the corresponding VRFB

(Fig. 3c and Supplementary Figs. 2–4). This reduction primarily reflects the distribution of power-related capital expenditure over greater energy capacity. Accordingly, the contribution of initial expenditure to LCOS decreases from 31.2% to 23.3%, whereas the share of electricity-related costs increases from 38.7% to 45.8%, despite remaining approximately €133 MWh^{-1} in absolute terms. Thus, longer storage duration reduces capital intensity, making efficiency and recurring operating costs increasingly important for further LCOS reduction.

Performance targets for cost-competitive flow batteries

Having established the baseline economic performance, we next examined how improvements in electrochemical stability and operating characteristics could further reduce storage costs. The degradation sensitivity analysis distinguishes electrolyte decay, crossover-induced capacity fade and calendar degradation (Fig. 3d–f). Both electrolyte decay and calendar degradation produce nonlinear increases in LCOS, whereas crossover-induced capacity fade has a comparatively modest effect over the investigated ranges. The baseline electrolyte decay and crossover fade rates of 0.0020% and 0.0018% per cycle, respectively, lie within regions of diminishing economic returns from further improvement. By contrast, the baseline calendar degradation parameter of 0.086% day^{-1} presents greater scope for cost reduction. Reducing this rate to 0.005% day^{-1} lowers the projected 4 h LCOS from €344 to €305 MWh^{-1}. Similar trends are observed for the 8 h configuration (Supplementary Fig. 5a–c), identifying calendar stability as a priority under the assumed operating and maintenance conditions.

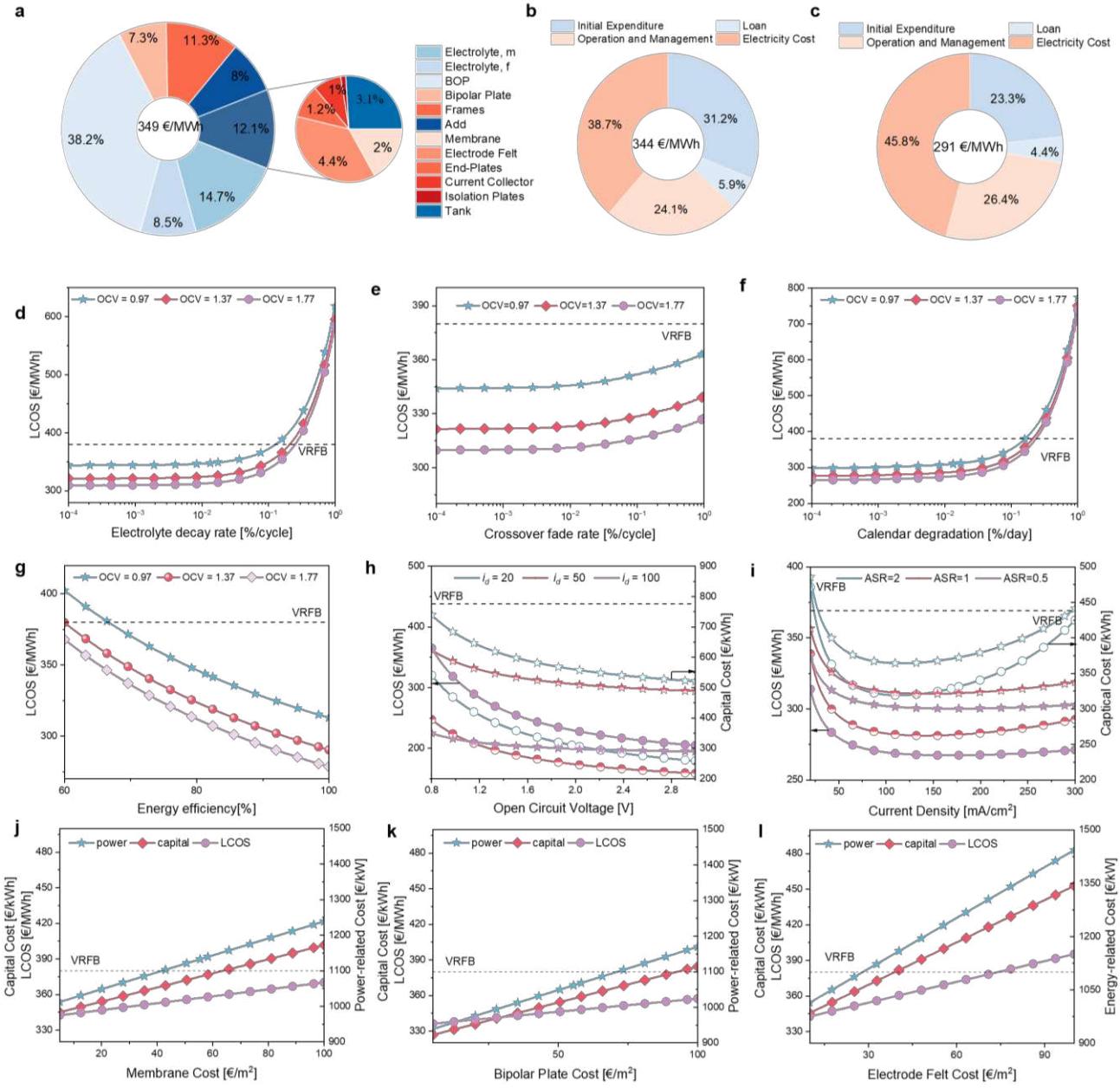


Fig. 3 Techno-economic assessment and cost sensitivities of S–Fe RFBs. a, Capital cost breakdown of the

modelled 1 MW/4 MWh S–Fe system, including major system components. **b,c**, LCOS breakdowns for the 1 MW/4 MWh and 1 MW/8 MWh configurations, respectively. **d–f**, Effects of electrolyte decay, crossover-induced capacity fade and calendar degradation on LCOS at different OCVs. **g**, Dependence of LCOS on energy efficiency at different OCVs. **h**, Effects of OCV on capital cost and LCOS at different operating current densities. **i**, Dependence of capital cost and LCOS on current density at different ASRs. **j–l**, Effects of membrane, bipolar-plate and electrode-felt prices, respectively, on power-related capital cost, total capital cost and LCOS. All results are based on prospective system-level modelling using experimentally informed parameters and the engineering and financial assumptions detailed in the Supplementary Information.

Beyond degradation stability, energy efficiency and cell voltage offer additional opportunities for reducing storage costs (Fig. 3g, h). Higher energy efficiency lowers LCOS by reducing electricity consumption, whereas increasing OCV decreases both capital cost and LCOS by increasing the energy obtainable per unit of active material and reducing the cell area required for a given power output.[10] However, the marginal cost benefits diminish at higher voltages (Fig. 3h and Supplementary Fig. 5e). Similar trends are observed for the 8 h configuration (Supplementary Fig. 5d). As the experimentally characterized S–Fe chemistry has an OCV of 0.97 V, the higher-voltage scenarios represent prospective redox chemistries rather than demonstrated improvements to the present system. Their economic benefits therefore depend on maintaining favourable efficiency, stability and material costs. Recent pH-decoupled aqueous RFBs exemplify higher-voltage operation while highlighting the need to manage crossover-induced pH changes.[31]

Current density and ASR introduce a further trade-off between stack expenditure and polarization losses (Fig. 3i). Increasing current density initially reduces the cell area required to deliver the rated power, lowering area-dependent component costs. At higher current densities, however, increasing polarization losses progressively offset these savings, producing an ASR-dependent minimum in LCOS. Lower ASR reduces this penalty and extends the economically favourable operating range towards higher current densities. Similar behaviour is observed for the 8 h system (Supplementary Fig. 5f). These results suggest that higher-current-density operation should be pursued alongside reduced cell resistance and maintained energy efficiency.

Component-price sensitivities reveal more limited opportunities for cost reduction through individual materials (Fig. 3j–l and Supplementary Fig. 5g–i). Lower membrane, bipolar-plate and electrode-felt prices reduce power-related capital expenditure, but their influence on LCOS is moderated by the substantial contributions of auxiliary equipment, electricity and maintenance. In particular, the assumed membrane price of €12 m^{-2} and its 2.0% contribution to capital cost leave little scope for further savings through membrane-price reduction alone. Improvements in membrane transport properties, selectivity and durability may therefore offer greater economic value than reductions in purchase price, provided that they improve efficiency or reduce lifetime operating costs.[21,32,33]

Combining these findings provides quantitative targets for future system development. Under the modelled conditions, reducing calendar degradation to 0.005% day^{-1}, increasing operating current density to 80 mA cm^{-2}, reducing polarization and improving usable capacity could lower the 4 h LCOS to €285 MWh^{-1} while maintaining an 81% round-trip efficiency. A further prospective scenario combining an OCV of 1.77 V, 86% round-trip efficiency and an energy-related capital cost of approximately €27 kWh^{-1} could yield an LCOS 35% below the 4 h VRFB benchmark. Applying the same performance targets and cost assumptions to the 8 h configuration gives a projected LCOS of €206 MWh^{-1}. These scenarios distinguish improvements potentially achievable through cell and component engineering from those requiring alternative higher-voltage redox chemistries, providing a basis for prioritizing future battery development.

Life-cycle environmental impacts of S–Fe RFBs

To examine whether the economic advantages of S–Fe RFBs translate into environmental benefits, we conducted a comparative LCA against duration-matched VRFBs, considering both cradle-to-gate and cradle-to-use system boundaries.[26,28] The former encompasses raw material extraction, processing and battery manufacturing, whereas the latter additionally accounts for operation and maintenance over an assumed 20-year lifetime. Eight environmental impact categories were evaluated to capture greenhouse-gas emissions, toxicity and resource depletion (Fig. 4).

For the 1 MW/4 MWh S–Fe system, manufacturing impacts are dominated by the catholyte and current collectors, although their contributions vary substantially across impact categories (Fig. 4a). The catholyte accounts for approximately 48% of GWP and 55% of FRS, whereas current collectors contribute more than half of TET, FET, MET, HT and MRS. In comparison, electrolyte production dominates GWP, TA, MRS and FRS for the VRFB, with current collectors also contributing substantially to toxicity-related impacts (Fig. 4b). Despite the lower cost of its active materials, the S–Fe system exhibits higher cradle-to-gate impacts in six of

the eight categories, with TA and MRS being the exceptions (Fig. 4c). Similar trends are observed for the 8 h configurations (Supplementary Fig. 6a–c). These findings indicate that material affordability does not necessarily correspond to lower environmental burdens, particularly when component production and material requirements are considered.

Including operation and maintenance preserves this overall ranking under wind-electricity charging (Fig. 4d–f). The 4 h S–Fe system exhibits a GWP of 61.38 kg CO_2-eq MWh^{-1}, 8.5% higher than the VRFB benchmark of 56.59 kg CO_2-eq MWh^{-1}. Conversely, its TA is lower, at approximately 0.27 versus 0.46 kg SO_2-eq MWh^{-1}. The relative contributions of manufacturing and operation differ across environmental indicators. Manufacturing accounts for more than 60% of S–Fe TET, whereas operation contributes approximately 60–65% of FET and MET. Maintenance generally makes a smaller contribution. These results identify complementary environmental priorities: reducing the manufacturing burdens of electrolytes and current collectors, while limiting the operational impacts associated with electricity consumption.

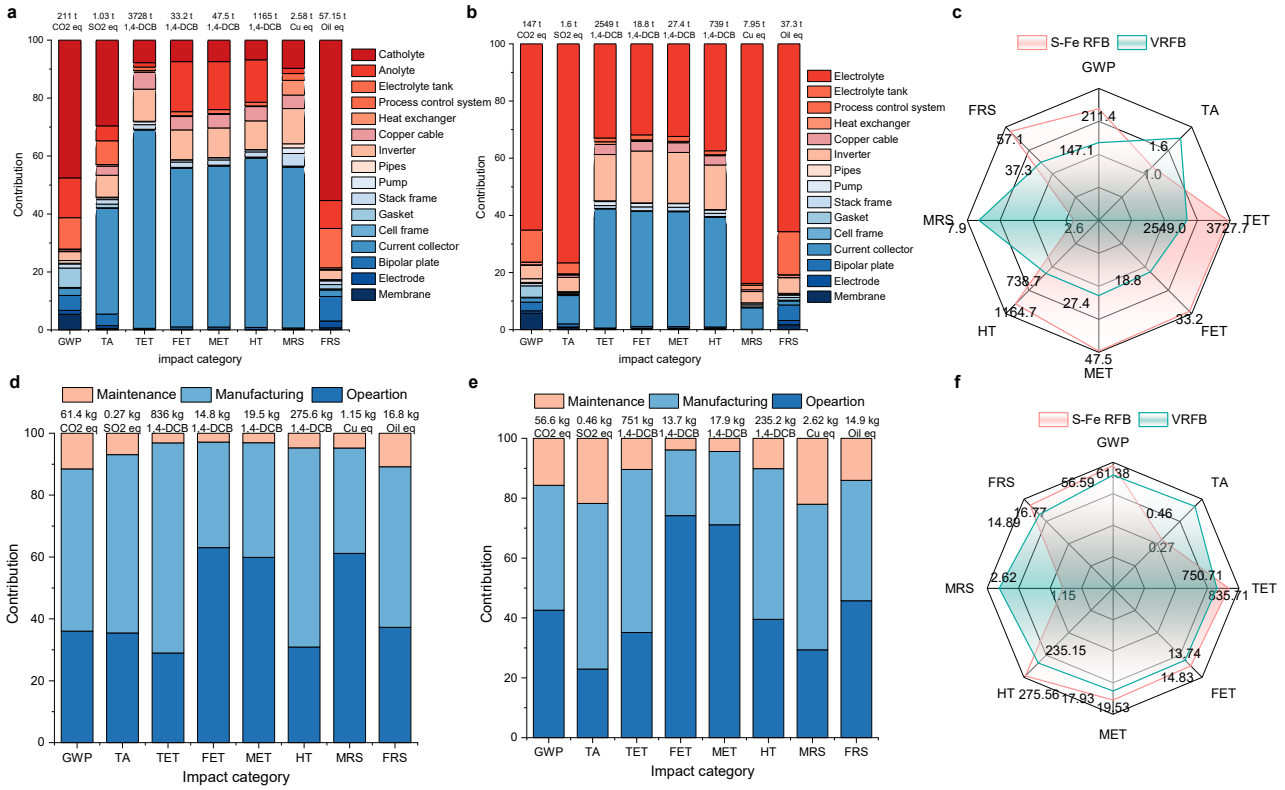


Fig. 4 Life-cycle environmental impacts of S–Fe RFBs and VRFBs. a,b, Cradle-to-gate environmental impact contributions of individual components in the 1 MW/4 MWh S–Fe RFB and VRFB systems, respectively. **c**, Comparison of cradle-to-gate environmental impacts per MWh of storage capacity between the two systems across eight impact categories. **d,e,** Relative contributions of manufacturing, maintenance and operation to the cradle-to-use environmental impacts of S–Fe RFBs and VRFBs, respectively, under wind-electricity charging over an assumed 20-year lifetime. **f**, Comparison of cradle-to-use environmental impacts per MWh of delivered electricity under wind-electricity charging. The eight impact categories are global warming potential (GWP), terrestrial acidification (TA), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), human toxicity (HT), mineral resource scarcity (MRS) and fossil resource scarcity (FRS).

Environmental sensitivities and design implications

The environmental performance of both technologies depends strongly on the electricity used for charging (Fig. 5a–h). For the 4 h S–Fe system, GWP increases from 61.38 kg CO_2-eq MWh^{-1} under wind charging to 160.74 and 585.58 kg CO_2-eq MWh^{-1} under PV and grid-electricity charging, respectively. Wind charging therefore reduces GWP by approximately 90% relative to grid charging. However, this advantage is not consistent across all environmental indicators. PV charging produces the highest TET, FET, MET and MRS for both technologies, whereas grid charging yields the lowest MRS under the modelled conditions. The relative environmental performance of S–Fe and VRFB systems also varies with the charging source. Although S–Fe exhibits higher GWP under wind charging, its GWP under PV and grid charging is approximately 2.5% and 6.8% lower, respectively, than that of the VRFB. These findings demonstrate that electricity-related

emissions strongly influence life-cycle GWP, while reductions in carbon emissions do not necessarily coincide with improvements in toxicity and resource-related impacts.

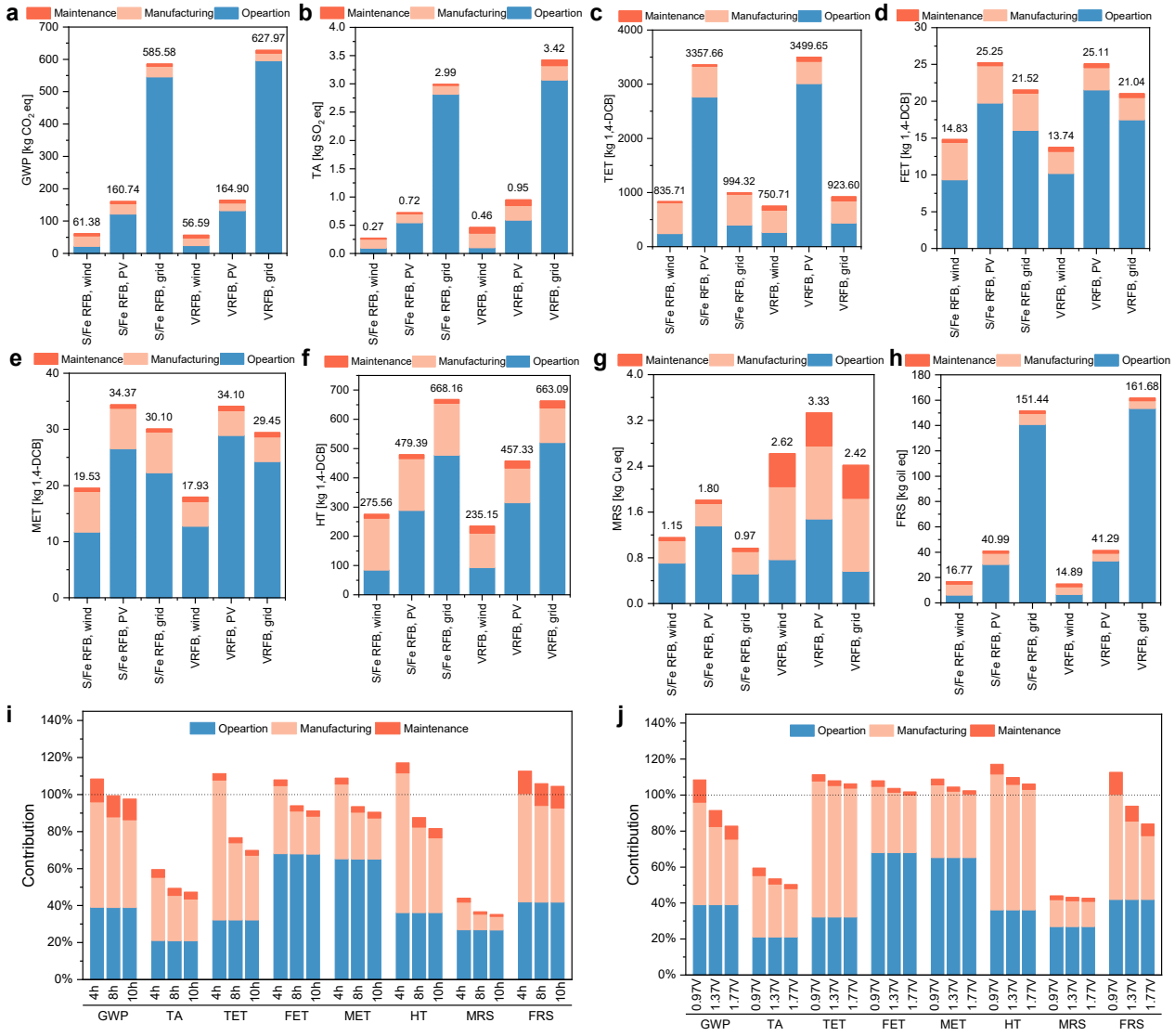


Fig. 5 Effects of charging electricity, storage duration and cell voltage on the life-cycle environmental impacts of S–Fe RFBs. a–h, Cradle-to-use environmental impacts of 1 MW/4 MWh S–Fe RFBs and VRFBs under wind, PV and grid-electricity charging, showing the contributions of manufacturing, operation and maintenance to (a) GWP, (b) TA, (c) TET, (d) FET, (e) MET, (f) HT, (g) MRS and (h) FRS. i, Effects of storage duration (4, 8 and 10 h) on the environmental impacts of S–Fe RFBs. j, Effects of increasing the assumed OCV (0.97, 1.37 and 1.77 V) on environmental impacts. In i and j, impacts are normalized independently to those of the 4 h VRFB benchmark under wind-electricity charging (100%, dashed line). Higher-voltage cases represent prospective modelling scenarios under the assumed material inventories rather than experimentally validated battery chemistries.

Extending storage duration reduces the environmental burdens per unit of delivered electricity, although the magnitude of improvement differs between technologies and impact categories (Fig. 5i and Supplementary Fig. 6d–f). Under wind charging, increasing S–Fe storage duration from 4 to 8 h reduces GWP from 61.38 to 56.26 kg CO_2-eq MWh^{-1}, an 8.3% reduction, while TET and HT decrease by 31.1% and 25.2%, respectively. The corresponding VRFB GWP decreases by 18.5%, from 56.59 to 46.13 kg CO_2-eq MWh^{-1}. Consequently, the 8 h S–Fe system retains higher impacts in six of the eight categories relative to its duration-matched VRFB benchmark, including a 22.0% higher GWP. When compared instead with a fixed 4 h VRFB benchmark, extending S–Fe storage duration to 8 or 10 h yields lower impacts in seven categories, with only FRS remaining higher (Fig. 5i). These comparisons highlight the importance of consistent storage-duration benchmarks when interpreting environmental competitiveness.

Increasing cell voltage provides a further prospective pathway for reducing environmental impacts (Fig. 5j). Raising the assumed OCV from 0.97 to 1.37 and 1.77 V progressively lowers the modelled impacts, primarily

through reduced material requirements and associated manufacturing and maintenance burdens, while operational impacts remain approximately unchanged under the specified assumptions. At 1.77 V, GWP, TA, MRS and FRS fall below the fixed 4 h VRFB benchmark, whereas toxicity-related impacts remain higher. **Importantly, these scenarios isolate the effect of cell voltage within the existing LCA framework, retaining the assumed material identities and production processes while adjusting material requirements.** Achieving such voltages would require alternative redox chemistries, potentially involving different active materials, synthesis routes and environmental burdens. The projected reductions therefore represent voltage-dependent modelling outcomes rather than validated environmental benefits of a higher-voltage battery chemistry. Establishing these benefits would require chemistry-specific life-cycle inventories alongside experimental validation of efficiency, stability and durability.[29,34]

Discussion and outlook

This study reveals a fundamental distinction between the economic and environmental competitiveness of emerging RFB chemistries. Despite their inexpensive active materials, S–Fe RFBs achieve only modest reductions in LCOS relative to VRFBs, while exhibiting higher life-cycle impacts across most environmental categories under wind-electricity charging. These contrasting outcomes highlight that material affordability alone is insufficient to establish the economic and environmental advantages of a storage technology. Instead, system-level performance depends on the combined effects of electrochemical efficiency, material requirements, degradation and lifetime operation.

The economic analysis identifies clear priorities for further development. Although the laboratory-scale S–Fe cell demonstrates stable cycling performance, calendar degradation remains a major source of projected lifetime costs. Improving calendar stability, together with reducing polarization and enabling efficient operation at higher current densities, could lower the 4 h LCOS from €344 to €285 MWh^{-1}. Further reductions are predicted for higher-voltage chemistries, with a prospective 1.77 V system reaching €206 MWh^{-1} at 8 h under the assumed performance and cost conditions. However, these projections should not be interpreted as demonstrated capabilities of the present S–Fe chemistry. Realizing such improvements requires advances in electrochemical stability, reaction kinetics and system engineering, while higher-voltage operation would require alternative redox chemistries with independently validated performance and material costs.

Environmental improvements require a complementary approach. The substantial contributions of catholyte production and current collectors to manufacturing impacts suggest opportunities for reducing material consumption and improving manufacturing processes. Longer storage duration decreases environmental burdens per unit of delivered electricity, but does not eliminate the disadvantage relative to duration-matched VRFBs. Moreover, the influence of charging electricity varies substantially across impact categories, emphasizing that lower carbon emissions do not necessarily imply lower overall environmental impacts. Importantly, the projected environmental benefits of higher cell voltage are derived from voltage-dependent sensitivity analyses that retain the assumed material inventories. Alternative redox chemistries may introduce different production routes and environmental burdens, requiring chemistry-specific LCA before their sustainability advantages can be established.

Translating these findings into practical deployment will require validation beyond laboratory-scale cycling. Long-duration operation, calendar ageing, component durability and maintenance requirements need to be established under representative operating conditions to reduce uncertainties in lifetime cost and environmental projections.[35] In situ and operando characterization can help distinguish electrolyte degradation from crossover and charge imbalance during such validation.[36] In parallel, future assessments should account for manufacturing scale-up, material sourcing, electrolyte recovery and end-of-life management.[26,27,37] Integrating these considerations with electrochemical development will be essential for identifying RFB designs that achieve not only lower storage costs but also demonstrable reductions in life-cycle environmental impacts.

Methods

The capital cost model is used to investigate S-Fe RFB expenditures at the investment level, which can be separately calculated as power-related costs and energy-related costs because of their unique ability to tailor power and energy separately.[11,25] Energy-related costs consist of electrolyte and tank costs (Supplementary Note 2), while power-related costs comprise reactor, balance-of-plant, and other additional costs (Supplementary Note 3). Employing a conservative approach excluding potential cost reductions stemming from scaling effects, the system costs are calculated by linearly dividing into energy-related costs C_E and

power-related costs C_P:

$$C_{capital} = C_E \cdot E_{b,nom} + C_P \cdot P_{b,nom} \quad €$$

The rated energy $E_{b,nom}[€/kWh]$ is the energy discharged by the battery at rated power, $P_{b,nom}[€/kW]$ [kW], during the discharge time $t_d[h]$. To model life-cycle costs, the LCOS is employed to compare the economic metrics of different storage technologies (Supplementary Note 4).[5,25,38] It considers the costs of manufacturing, installing, and operating a selected storage technology under specific financial assumptions over a defined period:

$$LCOS = \frac{I_0 + \sum_{t=1}^{N_y} \frac{I_t + C_{rep,t} + C_{O\&M,t}^f}{(1+r_{d,y})^t} + \sum_{t=1}^{K} \frac{C_{O\&M,t}^v + C_{O\&M,t}^{ch} + C_{el} \cdot E_{dis,t}(1+r_{i,d})^{t-2}}{(1+r_{d,d})^t}}{\sum_{t=1}^{K} \frac{E_{dis,t}}{(1+r_{d,d})^t}} \left[\frac{€}{MWh}\right]$$

where I_0 and I_t respectively denotes initial expenditure and annual payments, $C_{rep,t}$denotes the power-related or energy-related periodic replacement cost. $C_{O\&M,t}^f$, $C_{O\&M,t}^v$ and $C_{O\&M,t}^{ch}$ are annual fixed costs, daily variable costs and charging irreversibility cost, respectively. C_{el} is the specific cost of purchasing electricity and $E_{dis,t}$ is the useful discharged energy during the tth cycle.

Life Cycle Assessment is a standardized method for evaluating the potential environmental impacts of a product or service throughout its entire life cycle. The goal of the study is to conduct a comparative life cycle assessment of the S–Fe RFB system within a cradle-to-use system boundary, including raw material extraction, material processing, product manufacturing, and operation (Supplementary Notes 5–8). Given the lack of comprehensive inventory data associated with battery system performance during the long-term operational phase, considerable uncertainty remains. However, quantifying the environmental impact of long-term energy storage technologies including the operational phase offers a more systematic perspective. The functional units are 1 MWh of energy-storage capacity for the cradle-to-gate assessment (Supplementary Notes 5 and 7) and 1 MWh of electricity delivered over a 20-year operating lifetime for the cradle-to-use assessment (Supplementary Notes 6 and 8). Wind and photovoltaic (PV) electricity are considered, with the electricity mix for Europe without Switzerland used as the reference scenario (Supplementary Table 39). As the most well-developed aqueous RFBs, VRFBs are employed as a benchmark for comparison with S-Fe RFBs (Supplementary Notes 7 and 8). The environmental impacts are quantified using SimaPro 9.0.0.48 and the ecoinvent 3.6 database.39,40 Impact assessment uses the ReCiPe 2016 Midpoint (H) method,41 covering the following impact categories: global warming potential (GWP), terrestrial acidification (TA), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), human toxicity (HT, considering both carcinogenic and noncarcinogenic), mineral resource scarcity (MRS), fossil resource scarcity (FRS).

Author contributions

Methodology: S. Guan, R. Tan, Y. Qiao. Formal analysis: S. Guan, M. Chen. Investigation: Z. Feng, T. İnan, B. Uralcan, Y. Luo, R. Tan. Funding support: Z. He, R. Tan. Supervision: Z. He, R. Tan. Writing – original draft: S. Guan, R. Tan. Writing – review & editing: S. Guan, R. Tan.

Data availability

The model inputs and supporting analyses are available in the main article and its Supplementary Information. These include the model input parameters, techno-economic calculations, life cycle inventory data, and supplementary analyses.

Code availability

The Python code for the techno-economic assessment of polysulfide–ferrocyanide redox flow batteries, together with model parameters, execution instructions and example outputs, is publicly available on https://github.com/SiwGuan/Economic-competitiveness-of-S-Fe-RFB.

Competing interests

The authors declare no competing interests.

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