Final report

1. Project details

Project title	FerroBAT - Iron Flow Batteries for Maritime and Stationary Applications
File no.	640222-497109
Name of the funding scheme	EUDP
Project managing company / institution	Energy Cluster Denmark
CVR number (central business register)	41343788
Project partners	Energy Cluster Denmark, Siemens Gamesa Renewable (DK + DE) Energy, DTU Energy, SDU, DTU Wind and Energy Systems, Siemens Energy
Submission date	August 2025

2. Summary

Describe the objectives of the project, the obtained results and how they will be utilized in the future in English. The summary will be published on www.eudp.dk and www.energiforskning.dk.

Project summary:

The purpose of the project

The project and purpose were stopped at the premature project closure. The project initially aimed to develop an innovative energy storage solution based on iron-flow technology that could provide reliable long-duration energy to marine vessels and backup storage to the grid using non-toxic, environmentally friendly, cost-effective, and non-flammable iron-based electrolytes. Innovation in the use of water-soluble coordination complexes of iron would allow operation at circumneutral pH. This would represent a large non-iterative step that would have circumvented energy losses and the need to re-balancing cells because of plating and H2 evolution processes. Advantageously, this would simplify significantly stack construction. We aimed to attain a <100 €/kWh cost for the flow battery upon scaling-up.

The partners followed an application-oriented approach for a fast-track development towards TRL4-5 for the system. In addition to "all-iron all-soluble" new generation iron flow batteries (Gen 2), incremental improvement in the state-of-art all-iron flow battery (Gen 1.1) were to be investigated. A first detailed testing campaign was performed on a large-scale commercially available iron-flow battery (75 kW / 500 kWh) to achieve a deep

understanding of the system and improve upon the battery operation. A second long term test was planned but stopped at the premature project closure. A control strategy was in the making to be designed for the overall system to optimize operational efficiency and stability at the premature project closure.

Finally, attained innovation in cell design and chemistry would have been demonstrated through construction of a prototype power stack. KPI's of the assembled stack would have been validated against the calculated design values.

Results, conclusions and perspective

The project and purpose were stopped at the premature project closure. At the closure of the project in April 2025 the partners had reached the following results in the WP.

WP1: Management.

Siemens Gamesa had up to September 2024 as managing partner organized the project management together with Energy Cluster Denmark. SGRE withdrew from the FerroBAT project at the end of September 2024 due to strategic changes in the company and a shift in product focus. Energy Cluster Denmark has during the extension application period from September 2024 and closing period up to April 2025 organized and coordinated more physical meetings and online consultations between the partners in the steering and project management groups and the possible new partner Visblue in order to find solutions and partner roles for a project continuation or a termination. All partners were informed and participated of the process for a change request and possible onboarding of the new partner and informed with the risk for termination of the project. Consultations also included administration, budget control, time registration of partners and reporting as well.

WP2: Dissemination.

Public dissemination, LinkedIn posts were planned for the last part of the project.

Poster presentations:

- Nordic Redox Flow Battery Metting (NordicRFB) in Turku (Findland),
- C4 Contemporary Coordination Chemistry in Copenhagen (DK)
- 45th International Conference in Inorganic Chemistry (ICCC) in Colorado (USA).

Oral presentations:

- Understanding Iron and Friends Symposium in Darmstadt (Germany). "*Iron Complexes as Charge Carriers in All Iron Redox Flow Batteries*" (04/09/2024)
- Public presentations for IDA Elteknik (12/05/2025) and VandCenter Syd (16/06/2025) at the University of Southern Denmark (DK). "*The Future's Electroactive Molecules for Redox Flow Batteries*"

Publication:

Mathias L. Skavenborg, Mads Sondrup Møller, Robin M. Wessling, Johan Hjelm, Christine J. McKenzie, Highly-Soluble Iron Complex as Negolyte for all Iron Redox Flow Battery, (manuscript intended for submission to ACS Energy Letters, *in preparation*).

WP3: Hybrid All-Iron Flow Battery Improvement Potential

A set of flexible small scale (5 – 25 cm²) iron flow battery reactors with built-in rebalancing were constructed to investigate the improvement potential of the hybrid all-iron configuration. This cell type corresponds to the large-scale commercial battery that were tested in WP5 Strategies for mitigating the hydrogen evolution problem of the plated iron negative electrode were to be investigated

Due to the changes of partners and pause announced in the project the postdoc hired at DTU was partly transferred to another position and could only assist the project with a reduced number of hours. This led to a reduced effort on the all-iron hybrid battery chemistry and the efforts in the project were focused mainly on *supporting the scheduled ongoing activities in collaboration with SDU in WP 4. The project was though scheduled and planned in the labs at DTU and SDU and was conducted according to a reduced test plan. E.g. a backorder to an ordered special chemical compound was received late to be tested in the lab, which caused the lab to test also in period P4 before the termination. EUDP were given notice that the tests would continue in P4 in order to follow the project plan and reach evaluable results of the tests performed and not to cause any delays of the total project with the new partner.*

WP4: Next Generation All-Iron Chemistry

For the first period of the project the SDU group conducted a literature survey of aqueous iron chemistry culminating with the synthesis of around 12 iron complexes of different supporting ligands that are either novel (designed by Professor Christine McKenzie's research group), or commercially available. Electrochemical properties were evaluated using cyclic voltammetry, and water solubilities were measured for a rough guide as to their suitability as charge carriers for aqueous all soluble iron flow batteries.

In the period (01.09.2024 – 01.04.2025), spent time on the following activities:

The study was continued with selected promising complexes to ensure electrochemical reversible redox chemistry and further characterization using spectroscopic methods (MS, IR and NMR-spectroscopy, X ray diffraction). In addition, a completely difference class of complex that we predicted could be relevant was synthesized. This had been planned at least a half year earlier however it took a considerable time to have an unusual precursor chemical delivered due to customs restrictions in its country of origin (Republic of Czechoslovakia). We finally received it around August 2024 and the ongoing synthesis and characterization took around 3 months from then. A handful of complexes have been sent to DTU for further upscale testing in a flow battery setup. The tests at DTU are long-term cycling tests using small RFB like set ups. Experiments can last weeks, and limited equipment means they cannot be done in parallel. The feedback from the DTU group determines ongoing complex design and characterization.

Especially, the iron complex based on the chemical that took a long time to arrive is very promising for the role of a fundamentally different type and novel negolyte in flow batteries. This complex has the following three properties (i) reversible electro-chemistry within the stability window of water, (ii) high solubility (2 M) and (iii) two chemically stable (now for 3 months) oxidation states. This negolyte has been coupled with cheap iron salts, e.g., $FeCl_3$, and $K_3[Fe(CN)_6]$ as the posolyte and tested at DTU for applicability for use in a larger scale flow battery. Initial tests reveal a flow battery which a stable for up to 50 charge/discharge cycles. Patenting of this system will be considered when we know the results of longer charge-discharge experiments under various conditions.

Another system discovered a few months ago is also extremely promising and with novel IP. This needs more work that is now beyond the scope of this project. At this early stage we believe our approach at SDU developing new iron electrolytes will produce two new breakthroughs for the field.

DTU conducted lab-scale cell testing and collaborated with SDU on the characterisation of a new type of metal complex that fulfils the criterion of having very strong metal-ligand bonds, so strong that, in contrast to the few known systems using iron complexes, requires no excess ligand in the electrolyte. Excess ligand needed often for labile aqueous iron is one of the greatest sources of capacity fade. This was observed in the test campaign in the previous reporting period. The iron complex delivered by SDU (FeSAN) was tested with $FeCl_2$ present in both negolytes and posolytes to avoid Fe^{2+} cross-over through the ion-exchange membrane. This strategy is techno-economically viable due to the low cost of $FeCl_2$. The tests at DTU surprisingly showed very strong capacity fade, and tests of possible hydrogen evolution of the reduced iron complex did not show evidence of significant hydrogen evolution. A test campaign was initiated where the complex was tested with a mixture of $FeCl_2$ and $FeCl_3$ in the posolyte which yielded very low capacity fade for over 500 cycles, after which rapid capacity fade set in. Replacing the used posolytes with fresh 50:50 $FeCl_2$:$FeCl_3$ electrolyte recovered the capacity fully. A total of over 1500 cycles were collected in a test sequence involving posolyte replenishment two times. Metal complex containing negolyte was tested using voltammetry after test periods where the capacity had faded dramatically, and no change in the amount of electroactive FeSAN was detected. No FeSAN was de-tected in the posolytes after testing. This led to the conclusion that FeSAN is a highly stable molecule potentially capable of supporting very long lifetimes in a flow battery. All tests conducted in the project shutdown period were conducted in acidic iron chloride containing electrolytes. Even though our initial tests were unable to detect hydrogen evolution, we observed strong capacity fade in all tests conducted with FeSAN *where only $FeCl_2$ was used in the posolyte, while no degradation products were found after testing. These observations indicate that the cell was unbalanced (the redox state of the negolyte drifted during test and led to a decreasing amount of oxidized FeSAN available in the negolytes when fully discharged) and that this is the main cause of the observed capacity fade. By the time the project activities were concluded the process responsible for the unbalancing of the cell had not been identified.*

WP5: Commercial IFB Characterization & Modelling:

The scope of the work package was to acquire knowledge on the characteristics of the Iron Flow Battery, IFB 1) to confirm the operational advantages of the technology, 2) reduce the uncertainty of the technical performance and 3) to enable modeling of the battery power, energy and efficiency performance. Siemens Energy and Siemens Gamesa Performed a test round at the purchased commercially available ESS Inc IFB. An internal ESS IFB efficiency test report was produced by the SGRE partner for distribution among the partners. More ESS IFB longterm tests were planned with the partner DTUwind when the project came to a closure.

WP6: Stack design, assembly and testing.

Siemens Energy and the new onboarded partner had just begun the design at the premature project closure. Prototypes of flow frames were manufactured in various materials – both 3D-printed and milled prototypes – which were assembled with corresponding sealing gaskets purchased from different suppliers. Various materials and equipment were also acquired, such as 3D printing material, screws and bolts, as well as various hoses and pumping equipment, to test whether the stacks could contain the liquid within the system without leaking. The tasks were still ongoing, and SGRE's experiences were being transferred to Visblue – the new partner to be uonboarded.

WP7: The partner DFDS is prepared and has carried out preliminary studies including vessel and port identification, chemical, electrochemical reactions and environmental issues in the maritime environment, but the tasks were not initiated during the period. SGRE and ECD coordinated with DFDS during the period.

3. Project objectives

The project initially aimed to develop an innovative energy storage solution based on iron-flow technology that could provide reliable long-duration energy to marine vessels and backup storage to the grid using non-toxic, environmentally friendly, cost-effective, and non-flammable iron-based electrolytes. Integrating larger amounts of renewable energy in the energy mix in a cost-efficient manner is not only of great societal and environmental importance but is also required to fulfil national and international targets. Inflexibility of the existing electric grids is anticipated to impede massive penetration of intermittent renewable energy sources such as wind and solar power, and results in an increasing need for cost-efficient energy storage solutions. Redox Flow Batteries (FBs) are inherently well suited for large-scale energy storage due to the independently scalable power (stack and cell size) and energy (tank size) of such systems. They generally have long lifetimes, a round-trip efficiency of up to 85%, and can be used for most types of energy services. As the electrolytes are aqueous and the reactants are stored in separate tanks, FBs also display low self-discharge and a high degree of safety.
The most researched and commercialized FB technology is the vanadium FB (VFB). The suitability of VFBs for energy storage services in conjunction with wind power has been demonstrated by e.g. Sumitomo Electric Industries[1]. Vanadium flow batteries suffer from high cost, significant price volatility, it is a limited mined resource, and some vanadium compounds are toxic. Current VFB systems use highly acidic electrolytes and fluorinated cell components, such as the ion-exchange membranes used to separate the positive and negative side electrolytes in the reactors, further adding to cost and environmental concerns.
All-iron flow batteries (IFBs) have recently emerged as a competitor to state-of-the-art VFBs. This type of battery is built with non-toxic, low-cost and earth abundant components. The state-of-art electrolyte used in the all-iron flow battery consists of a mildly acidic water solution of iron chloride (pH 2 – 4). IFBs are currently in early commercialization stage with only one company providing commercial systems (ESS Inc.). However, variations of iron-flow chemistry are closely investigated for application by e.g. VoltStorage and Fraunhofer ICT[2]. The technology is particularly promising for realizing the cost targets reported by LDES Council which

enables a total market size of 1.5 to 2.5 TW (85 – 140 TWh) long duration storage[3], as the iron-based electrolyte can cost as low as 20 €/kWh.
A major difference of IFBs from the standard redox flow technology is that the state-of-art all-iron flow batteries rely on reduction of iron ions (Fe^{2+}) to iron metal (Fe^{0}) on the negative side, leading to electrochemically driven deposition/stripping of metal deposits inside the reactor during charging/discharging. Specialized handling is required to maintain the electrochemical performance of the battery amid metal plating cycles which accompany side-reactions that generate hydrogen gas. This requirement leads to lowered system efficiencies as well as higher complexity of the system.[4,5,6]
This project aimed at the development and application of a high-performance, cheaper, and more sustainable alternative flow battery technology based on iron flow chemistry. Detailed characterization of commercially available systems will be implemented and exploited for better understanding of the system operation and areas of further development. An improved flow chemistry would be defined that imposes less stringent requirements on the battery system. Finally, a pilot-scale stack based on the proposed flow chemistry will be designed, assembled and validated against target KPIs provided by the application in marine industry and for stationary applications.

The project had three main objectives:

1. ***Deep Understanding of IFB technology***
   - *Testing of commercially available all-iron flow battery at SGRE Brande Brint Test-Site: gain operational experience and assess technology status.*
   - *Lab-scale testing of the new cells assembled by DTU Energy as basis for modelling and upscaling of the technology: KPIs such as: pressure drop, current densities, flow rate vs. efficiency.*

2. ***Innovation in Iron Flow Chemistry***
   - *Identify and monitor critical success factors in employing iron flow batteries. With the expertise of multiple DTU departments the goal is to understand the battery technology as well as ESS.*
   - *Determine the improvement potential of the state-of-the-art hybrid all-iron flow battery, for increased energy density, reduced system complexity, and improved efficiency, through advanced electrolyte engineering.*
   - *Design, synthesize, and test a new group of iron coordination complexes as active materials for an all-soluble all-iron flow battery and bring a selected system to lab scale demonstration. An all-soluble iron based flow battery chemistry holds promise for reduced system complexity and reinstates the advantageous decoupling of power and energy, in contrast to the hybrid systems.*

3. ***Stack Development for Marine and Stationary Storage Applications***

- *Suitable pilot-scale stack to be assembled and tested based on chosen flow chemistry after decision point in project.*
- *Application analysis of developed stack with new iron-flow technology in this project as well as state-of-art IFB:*
  - *Compliance to grid requirements and key performance characteristics for stationary land based large scale storage.*
  - *IFB integration in marine applications, vessel integration analysis, high level risk and hazard evaluation, hybrid vs all-soluble systems.*

4. Project implementation

The Project generally followed plans in all WP up to August 2024. Some delays occurred due to a backorder to an ordered special chemical compound was received late to be tested in the lab of WP4, and due to a transport damage to the ESS commercial IFB a new IFB had to be shipped and installed, before testing could be performed. WP2 Dissemination, and WP7 Maritime Implementation was all planned and prepared at the final stages of the project. The Maritim Partner DFDS had identified a *vessel and or a port for implementation of the IFB However major changes occurred when SGRE withdrew from the FerroBAT project at the end of September 2024 due to strategic changes within the company and a shift in product focus. A new managing and lead partner was to be onboarded. A process of onboarding a new partner company occurred during 2024 and April 2025 until the project and purpose were stopped at the premature project closure.*

5. Project results

- *The project and purpose were stopped at the premature project closure.*
- *Status is presented in "Results, conclusions and perspective"*

6. Utilisation of project results and Project conclusion and perspective.

- *DTU energy and SDU did reach promising results at TRL 3-4 level in finding electrolytes with the efficient electrochemical characteristics as presented in "Results, conclusions and perspective"*
- *DTU and SDU can based on the promising results continue into more scientific oriented projects and programmes with more lab tests. A new research project could be described. Scientifical Internationally the project has reached new important IFB insights, and it has potential to bring the partners into a forefront business case. The IFB is still a nontoxic power storage solution, however more investigations and developments need to be performed*
- *A promising stack design was in the making but was never tested. The onboarding partner Visblue were in the process with Siemens Energy of preparing design, production and test for a commercial large and medium scale IFB.*
- *Commercial IFB development would have to be based on the DTU-SDU continued projects.*
- *The partners are all prepared to continue the project in a later phase.*
- *A post doc, Mathias Lander Skaveborg, was employed by SDU the project. He has given guest lectures on the application of redox active iron complexes in redox flow batteries. In addition, he has demonstrated electrochemistry in KE801 laboratory exercises. His exceptional level of engagement has sparked the interest of younger students and attracting a MSc and a BSc who are working on RFB projects. It is no understatement to say that this grant is the reason that this activity has been initiated at SDU. We are using the results as a basis for applications to DFF for further funding.*