Publishable Phase 2 Final Report

Sustainable Single LiQuid flow battery (SLiQ)

August 2025

Acknowledgements

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Executive Summary

Summary of work achieved

We have delivered a first-of-a-kind long duration energy storage (LoDES) demonstrator using our innovative single liquid flow battery (SLiQ) that is based on lithium polysulphide chemistry. The system is installed in a local micro-grid that allows the sub-systems and functionality to be rigorously tested in a real environment. One of the key building blocks of the system is the pack, which is similar to a lithium-ion battery module in terms of functionality and modularity. Our packs are discrete units housing up to 16 cells with flow and electrical connections, battery management system and sensors. The demonstrator system consists of 5 packs that form a system when connected with a liquid catholyte tank and balance of plant including the power conversion system.

Besides having an installed demonstrator system, one of the key outcomes has been scaling our inhouse manufacturing capability and overcoming the challenges associated with producing repeatable and high-quality battery cells and catholyte to build full scale systems.

Technical progress

- Development of the unique spiral flow cell concept from small-scale, manually wound and assembled cells (S cells) to a production level cell product (L cells) with volume manufactured components and a scalable winding process.
- Design and build of an inhouse cell manufacturing line (V2 winding machine) that produced repeatable high quality L cells for the demonstrator system.
- Inhouse design and assembly of cell packs into serviceable units that form the key building block of the system and provide a future route to certification.
- Overall system design for safe transportation and future certification as a cargo transport unit. This design was reviewed independently by a dangerous goods safety advisor.
- Destructive cell testing according to standard nail penetration tests showed that we have developed a safe cell and electrochemistry. There was no visible reaction, minimal temperature increase, no fire or explosion, and no venting of gases.
- Development of an optimised and non-flammable catholyte that continued to provide the desired performance in terms of current and energy density while balancing longevity and cost.
- Scaling of inhouse catholyte manufacturing from lab scale batches of 0.5L to pilot manufacturing using 50L batch reactors. We engaged extensively with industry experts to develop best practice processes.

- The inhouse development and assembly of standardised test rigs to facilitate the full spectrum of cell testing from multiple coin cells to full scale systems.
- Control and monitoring platform was developed in line with industry standards and off-the-shelf components. The quality of power delivery from the demonstrator was tested according to IEC standards and surpassed the requirements for G99 type testing.

Battery performance

The SLiQ demonstrator system has met all of the performance requirements of the competition as follows:

- Long 10 hour discharge duration
- Minimal self-discharge of 0.02% over 4 hour storage periods during normal operation
- High round trip efficiency of 91% (DC coulombic)
- Minimal long term self-discharge rate of <0.1% catholyte charge loss when catholyte is stored separately to the cells
- High charge rate of 0.33C (fully charged in 3 hours)

Lessons learned

Scaling of manufacturing from TRL5 (development prototypes at small scale) to TRL7 (operational prototype alpha product) has been achieved as well as consistency and quality of cell production resulting in deep inhouse expertise which enables effective planning for the next steps to scale up. We have tracked and documented extensive lessons learned throughout the project to support scale up activities.

Route to commercialisation

The LoDES demonstrator system is our alpha product prototype that will be rigorously tested to provide meaningful data for third party verification and validation. This is a key step towards delivering beta systems at scale within our target markets. Throughout the project, we have explored key areas to help establish the route to commercialisation including; certification, carbon lifecycle, supply chain and detailed product costing. During the project we worked with consultants to establish which market roles StorTera could adopt for market entry and have engaged with multiple project developers for renewable energy co-location. The data that results from the LoDES demonstrator project will be used as evidence to meet customers’ due diligence and employers’ requirements with a view to deploy beta systems in key target markets. We already have commercial sales of lithium-ion battery systems for commercial and industrial applications. By establishing a customer base, developing inhouse expertise and a strong reputation, we are building a platform to transition from lithium-ion to SLiQ technology once we have demonstrated the bankability of the SLiQ.

Engagement for scale up

A key objective of the LoDES project was to identify the supply chain partners required for the supply of materials at scale. Many of the raw materials are deliberately taken from the lithium-ion industry, which gives us multiple supply chain options and provides pre-processed materials for cell assembly. The development of an inhouse pilot cell manufacturing line using standard roll-to-roll techniques has been informed by leading industry expertise.

The learnings from this pilot line are essential inputs for a third-party equipment engineering provider to develop a larger scale cell rolling machine for mass manufacture.

The scale up of manufacturing catholyte has been informed by leading experts to help develop production processes and batch quality testing. Our approach of identifying manufacturing partners for processed materials enables the setup of lean assembly manufacturing inhouse. This provides a de-risked business strategy that protects our background IP and requires less working capital to set up footprint factories.

Figure 1: SLiQ cells connected in a pack

Introduction

StorTera was awarded funding from the Department for Energy Security and Net Zero (DESNZ) to carry out a Phase 1 feasibility study followed by Phase 2 delivery of a long duration energy storage demonstrator. The project was funded through the Net Zero Innovation Portfolio under Stream 2 of the Longer Duration Energy Storage competition.

The competition aimed to deliver first-of-a-kind longer duration storage prototypes and required technologies to increase technology readiness level (TRL) by a minimum of 2 levels.

The minimum requirements for project eligibility were as follows:

- Must charge using electricity.
- Must be able to charge for at least 4 hours.
- Demonstrate the ability to remain charged for a period no less than 4 hours, without significant self-discharge, before utilising the stored energy, either as heat, electricity, or to displace an alternative carbon-intensive energy carrier.
- Must have the flexibility to increase electricity demand at times of low demand and high renewable output.
- Must be stationary – i.e., operate from 1 primary location.

This report summarises the work undertaken by StorTera during the project and demonstrates how the project goals have been achieved.

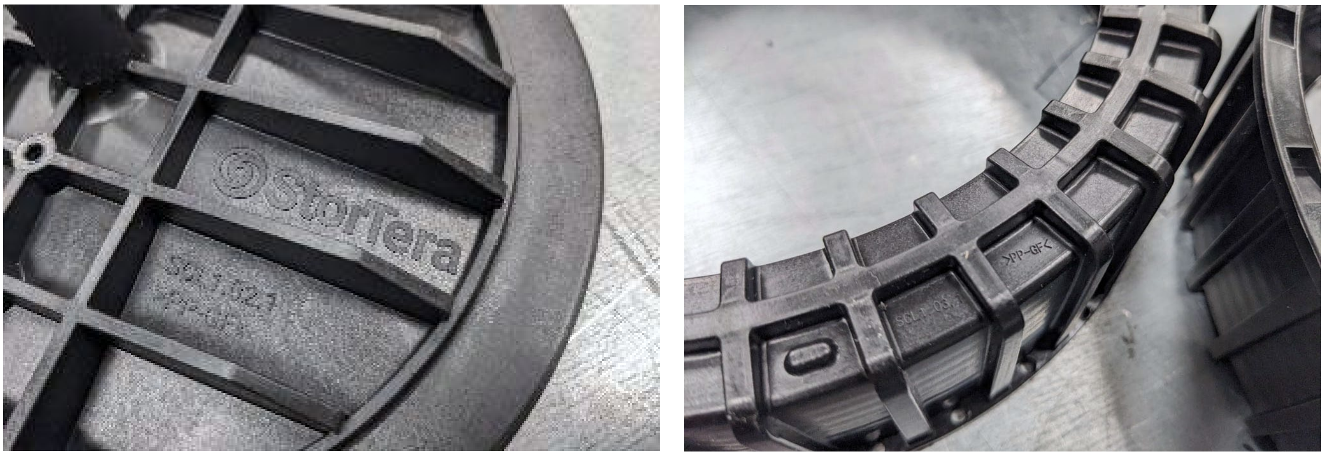
Design and manufacture of system components

Cell design

Unlike a traditional flow battery planar power stack, StorTera's innovative cylindrical flow cells are self-contained, sealed units, conceived and developed to enable low-cost volume manufacture. During the course of the project the flow cell concept was successfully taken from small-scale, manually wound and assembled proof-of-concept cells, right through to a production level cell product with volume manufacture ready componentry with a well-developed winding and build process work-flow which is ready for scaling to the next level.

Cell casings and internal components were iterated, simulated and tested multiple times at small and large scales to arrive at a robust mass-manufacture ready injection moulded design with low unit cost that can reliably hold internal pressures in excess of design requirements. Flow paths and connections were optimised and simplified using a combination of computational fluid dynamics (CFD) and extensive physical testing to ensure even flow distribution, minimised back-pressures and simplified low-cost connection points to external pipework.

Figure 2: Part identification and material composition markings to aid end of life recycling



Cell Manufacture

Throughout the course of the project, the cell configuration evolved in response to both optimisations from the electrochemical testing of prototype cells and in response to manufacturing challenges brought about by the spiral architecture and by the manufacturing processes used to create it. Changes like this meant machine configuration had to continuously evolve to accommodate changes to cell layers and different sealing configurations.

The ‘V2 winding machine’ was designed as a development platform from the outset and rapid iteration of cell production methodologies would not have been possible if the machine had initially been made too compact and with no facility to add shafts or additional control/sensing hardware. A conscious effort was made to have multiple configurable shaft positions, a wealth of spare mounting points and easy cable runs.

> *This flexible design approach allowed various experimental web handling hardware to be quickly trialled with low capital costs.*

Extensive use of 3D printing and in-house machining allowed development of technically sophisticated web handling features such as web sorting, displacement guiding, and ‘webbing-up’ fixtures which would have otherwise been expensive and time-consuming mini-development projects with third-party providers. This was all achieved whilst making everything installable and usable through gloves.

Pack design and manufacture

A key element of the SLiQ system is the development of the ‘cell pack’ concept. The pack is a modular grouping of cells into one self-contained unit with a minimum of external connections to a wider SLiQ system. These ‘packs’ form the building blocks from which SLIQ systems are composed.

This grouping together of cells into packs has many distinct advantages; simplifying electrical and flow connections, enabling modular and streamlined assembly of manageable sized units during manufacturing and importantly allowing the pack to become the minimum serviceable unit of larger systems, allowing a live system which has a faulty cell to be quickly brought back online by a relatively simple on-site pack swap.

Figure 3: A complete pack assembly being mounted into the test system

S1 System design & manufacture

As the overall 'packaging' for the SLiQ flow battery, the design of the S1 System (the fully packaged, turnkey SLiQ battery) for the project demonstrator and future scaled work has been continually re-assessed throughout the project. The packaging strategy targeted at project outset was re-evaluated in response to not only learnings from early prototypes of multi-cell systems, electrical architecture revisions and changes to proposed balance of plant (BOP) componentry, but also to continually evolving conditions in the wider commercial market for battery energy storage systems. Notably, a gradual shift towards the use of standard ISO multi-modal shipping container dimensions and footprints with the goal of simplifying logistics, civil works and site installations; an additional benefit comes from a specification point of view and when comparing competitor offerings.

Figure 4: Rendering of SLiQ containerised module

As a result, the design hierarchy of the SLiQ System was tweaked to take advantage of the benefits of this standardisation around shipping container dimensions, whilst still retaining the intrinsic modularity envisioned at project outset.

Catholyte Development

The catholyte is the unique-selling-point and differentiator of the SLIQ as it enables the energy and power qualities of the SLIQ to be decoupled. With the SLIQ hybrid flow battery chemistry, energy capacity can be simply increased through the storage of enhanced catholyte volumes in external storage tanks.

> *During the project, the catholyte formulation was developed significantly to suitably address the balance required between high current and energy density performance while addressing safety, longevity and cost considerations.*

During the project, three major generations of catholyte were developed, and the third generation was scaled for use in the demonstrator system. The primary differences between the different generations relate to the solvent systems utilised; polysulfide and inorganic salt concentrations were optimised throughout.

Catholyte Manufacture

The catholyte is the key active component which enables the SLIQ flow battery chemistry. During the project, the catholyte was scaled from small-scale <100 ml batches in the lab, to large-scale >50 L batches in a pilot manufacturing facility. This process involved the development of rigorous quality control methods to ensure the consistency and quality of the catholyte produced.

Catholyte manufacture was scaled from small <100 ml batches using lab glassware, to larger <1 L batches using lab glassware, to intermediate <5 L batches using a lab-scale reactor, to >50 L batches using a large-scale reactor and pilot manufacturing facility. StorTera engaged with external contractors to support the scaling efforts, but final pilot-scale manufacture for the demonstrator system was completed in-house at StorTera.

As with any scale-up process, significant development was made during the project regarding process scaling, optimisation, and improvement.

Balance of plant design and manufacture

Internally known as the "flow system", the balance of plant (BOP) design for the SLiQ battery has been developed as an adaptable framework design which can be applied, with only minor specification changes, to small lab scale cells right up to large SLiQ systems with multiple packs of cells. The overall flow system is comprised of smaller subsystems which can be modified to suit the target system capability and capacities required.

The design and manufacture of the flow system required solutions that were both simple, robust and low cost to ensure the future cost effectiveness of the product and final route to market. The liquid catholyte's unique composition meant that many of the common materials that would normally be used in typical balance of plant closed loop systems were not suitable for use. The catholyte's conductivity was also a limiting factor which restricted material choices for much of the flow system to non-conductive materials for safety.

Aligning with standard product development principles, cost reduction, performance and efficiency improvements and safety in design were all key areas of focus in the development of the BOP for the SLiQ battery in this project. To achieve these goals, rapid prototyping, simulations (structural and CFD) and lean engineering techniques were used throughout. In-house manufacturing capabilities & processes were developed and enhanced, with the building of relationships with UK suppliers & supply chains specifically targeted to provide materials and components sourced from within the UK and EU wherever possible. Building of these local relationships was especially useful when it came to specialist technical consultations and for staff training and techniques.

Electrical system design and assembly

The electrical & control system of the SLiQ Battery is the brain of the system which integrates all other sub-systems allowing them to function seamlessly together. Within the project timeline a fully scalable electrical & control system was designed and developed with functionality demonstrated throughout the project at various test stages and in the final demonstrator.

The final system architecture is flexible and scalable which is in line with the modularity and envisaged scale up of the SLiQ system. A flexible, cohesive architecture has been developed and deployed as part of this project which will allow for future scale up.

The SLiQ final system architecture has been designed to be flexible and scalable. As the SLiQ system operates on an electro-chemical cell basis, the heart of the system has been developed around technology utilized within industry leading lithium-ion systems but customized to be made appropriate for the lithium sulfur flow battery environment. Deciding on a customization focused architecture has provided the benefit of not requiring development of advanced power electronics for the sole use of this system, however limitations from this approach can apply which needed to be mitigated to ensure the safe and effective delivery of the S1 system demonstrator.

Demonstrator testing

Test results

The test plan for the SLiQ system was derived according to the requirements of the LoDES demonstration competition criteria. An overview of the test results is given as follows:

Table 1: SLiQ demonstrator test results summary

Demonstration Success Criteria	Measurement	Result
First-of-a-kind energy storage demonstration using innovative storage technologies	Outline key innovations	Lithium Sulphur technology combined with low cost roll-to-roll manufacturing High efficiencies maintained throughout the lifetime using novel maintenance regime that refreshes the catholyte Modular concept of systems that once connected together create large scale systems for long duration applications Low self-discharge rates due to Catholyte stored separately from cells while idle
Build and commission	System built and commissioned	Successfully built and commissioned a prototype demonstrator.
Planning consent and grid connection	System installed with permissions in place	System installed & Grid connected with Grid connection approval.

Achieve TRL 7 Alpha product demonstration in an operational environment - “tame” client or user site Functions, systems and interfaces integrated for monitored trials Validate in-use performance Features for installation and maintenance procedures Exposure to influences in user environment Manufacturing steps and repeatable samples	System installed in a real operational environment System grid connected and energised Demonstrate integration of all systems – mechanical, flow, electrical and controls Compare system performance to expected performance Assess installation and maintenance processes Demonstrate manufacturing plan and repeatability for cells and electrolyte	System installed in an industrial estate All subsystems integrated and functions verified System energised and Grid Connected In-use performance was validated using real life use cases of charging, discharging, remote monitoring & control and flushing to refresh the cells System performance compares well with individual cell tests Modularity of the design enabled easy installation and maintenance processes Manufacturing plan and repeatability of cells demonstrated Catholyte manufacturing scale up demonstrated Quality control and Installation methods developed & implemented in demonstration system
Minimum 4 hour charge duration	Show battery charging for >4 hours	Achieved ~ 10 Hour Charge Duration
Remain charged for more than 4 hours without significant self-discharge	Self-discharge rates at >4 hours	Reversal effects of self-discharge demonstrated using Flushing mechanism Self-Discharge % without flushing is 0.02% over a 4.5 Hours period

Utilise the stored energy as electricity	Show battery discharging to grid (discharge cycling)	Demonstrated battery discharging back to the grid
Flexibility to increase electricity at times of low demand and high renewable output	Respond to a control signal to charge battery from grid (charge cycling)	Charge, Discharge, Change of Power & Current demonstrated using remote control signals
Charge power consumption	Maximum charge rate	0.33C
Round trip efficiency	System efficiency (%)	91% DC Coulombic Efficiency
Ramping Time	Charge and discharge ramp rate %/s	100%/s - dictated by PCS,
Self-discharge rate	% charge loss per month	<0.1% Electrolyte charge loss when stored separately

Safety in design

Transportation

The transportation of SLiQ systems was a key area which had substantial bearing safety in design considerations. Engagement with a Dangerous Good Safety Advisor (DSGA) and the various investigations that followed were crucial to decisions around safe and legal transport of not just the demonstrator SLiQ system but for future scaled up systems.

The use of an outer enclosure which can be readily certified (at the appropriate stage of technical and commercial development) such as an ISO standard container frame was deemed a sensible and relatively future-proof route to ensure future classification as a Cargo Transport Unit (CTU) is possible. Likewise, the use of pre-approved and UN certified vessels to act as the main system tank(s) (or a custom tank which is then certified) was determined to be the least arduous path to allow full factory acceptance testing (FAT) of manufactured systems and safe transportation of any system with fluids on-board - avoiding any chemical handling operation on customer sites.

The continually evolving nature of regulations, certification and best practices for battery cells and systems, in addition to existing and still under-development guidance specific to flow batteries from the likes of the Institute of Electrical and Electronics Engineers (IEEE), mean that transportation regulations, particularly ADR, will be one of the first areas to be consulted prior to any significant changes to system design.

Figure 5: Photo of StorTera battery system

Destructive Safety Testing

To assess the operational safety of a SLIQ cell, an extensive testing programme was carried out to implement nail penetration tests. The purpose of the nail test was to assess the safety of the flow battery cells, specifically focusing on destructive testing. The nail penetration is considered to be the most extreme battery safety test, and provides a critical method to evaluate worst-case failure scenarios. The results of the nail penetration test were very positive with no incidents of fire, smoke or explosion observed. A "safe" result in a nail penetration test typically involves a contained reaction without any temperature increase, no fire or explosion, and without venting of gases. The specific thresholds for the safety standards were adapted form relevant standards (IEC 62133_2:2017+A1;2021, IEC 62619_2021, SAE J2464:2009. SAND 2005-3123). For a novel chemistry, demonstrating behaviour significantly less hazardous than conventional Li-ion under the same test would be a strong positive result. The conclusion of the tests was that the SLiQ battery cells demonstrated promising safety characteristics under severe internal short circuit conditions and even recovered their voltage once the nail was removed.

Route to commercialisation

SLIQ certification

StorTera worked with a consultant to assess a suitable way forward for the SLIQ in terms of commercialisation and certifications that would facilitate successful market entry. Technical evidence/benchmarked data was supplied to a consultant for assessment enabling them to highlight any gaps and areas to focus on as StorTera prepares to commercialise the SLIQ.

The results of the study recommended that StorTera prioritises assurances and design information including:

- Evidence for technical distinguishing features such as lifetime efficiency etc.
- Technology qualification by a third party in accordance with standards such as DNV-RP-A203.
- Fire safety in accordance with standards like NFPA 855 and UL 9540A.
- Compliance with disposal and recycling regulations (such as The Batteries and Accumulators (Placing on the market) Regulations 2008 and Waste Electrical and Electronic Equipment Regulations)

The report suggested that certifications should be postponed until design and manufacturing procedures are finalised but highlighted the necessary certifications that would facilitate the market entry of the technology.

> *Instead of certification at this stage, our consultant recommended alignment with Lloyds for product certification at an early stage following design freeze in order to make full certification easier in future as the tests are time consuming.*

Through the recommendations and discussions that have taken place with consultants and Lloyds Register, it is understood that a Technology Certification is the most appropriate first level of certification that would be required for the SLiQ system. It was also recommended to do an Integration Assessment prior to engaging Technology Certification to identify the TRL levels of different subsystems. This framework provides a systematic measurement for integration between system components and the outcome of the process will provide an array of different levels of integration between various components based upon knowledge, experience of previous integration, performance or other documented evidence.

Obtaining certification through Technology Qualification is an 8 month – 2 years process and requires the use of accredited test facilities for testing. The qualification confirms the readiness of the technology for deployment within the intended operating environment and is valid for 5 years.

Before certification through Technology Qualification is carried out, it was recommended by Lloyds Register to get a lower-level certification called “Approval in Principle”. Approval in Principle (AiP) is intended to provide technology developers with early confidence that their technology is capable of being appraised against existing codes and standards. The AiP explores if the technology meets to appropriate regulatory requirements and identifies any operational environment requirements or limitations.

At present, engagement has begun with Lloyds register to obtain an AiP, and following AiP, the certification through Technology Qualification will be carried out with an intention on getting relevant IEC & UL certification in the coming years.

Grid Services

StorTera undertook analysis into what grid services the SLIQ demonstrator could provide during testing. Scottish Power Energy Networks (SPEN) are the electricity distribution network operator (DNO) in Central and Southern Scotland, where the SLIQ will be installed in 2025. StorTera HQ is located in the Portobello GSP and the Kaimes constraint management zone (CMZ).

Four different grid service mechanisms were identified as feasible at HQ as follows:

- SPEN Flex;
- Local constraint management;
- Demand flexibility service; and
- Arbitrage.

Details of each one are provided in the following sections.

SPEN Flex

SPEN are the electricity DNO in Central and Southern Scotland, where the SLIQ will be installed in 2025. The SLiQ can be operated to provide flexibility services to SPEN, which involves operating the asset in a way that is beneficial to the network, reducing the need in constrained areas for traditional network reinforcement. Constraints on the electricity network are confined to specific locations, known as Constraint Management Zones (CMZs), and the DNOs run competitive tenders to procure the required amount of flexibility services for each CMZ. There are four types of flexibility services defined, which support the network under different conditions e.g post-fault or during peak load. The prototype system proposed at Peffer Place, Edinburgh is located within Portobello GSP of SPEN area.

Since June 2024, SPEN have been releasing tenders for their flexibility requirements on a month-by-month basis, via the Piclo Flex platform. Piclo Flex is an end-to-end platform for the procurement, dispatch, verification and settlement of flexibility services. SPEN publish their flexibility requirements for specific areas on the first working day of a month, for service windows in the following month. Bidding is open for one day only in the middle of the month.

StorTera has added the SLIQ demonstrator system at StorTera HQ as an asset on the Piclo platform, and completed the pre-qualification process for SPEN, making StorTera eligible to submit bids for future flexibility service requirements in this area.

Local Constraint Management

The Local Constraint Management (LCM) is a new service developed by the National Energy System Operator (NESO) to try and provide support to the heavily constrained B6 Transmission boundary between Scottish Power Transmission and National Grid Transmission. Due to the expected growth in renewable energy deployment in northern Scotland, the new power transfer expected could surpass the design limits on the existing transmission line before new supporting lines can be constructed. The LCM Service is part of NESO's 5 point plant to help tackle the B6 constraints without causing undue rises in costs that NESO believe would arise from just relying on the Balancing Mechanism (BM) to deliver the support. The LCM service can be accessed through the same Piclo Flex platform as the DSO services, meaning the SLIQ unit is also being pre-qualified for this service through that platform. Recent changes from the NESO such as allowing LCM providers to opt out of Applicable Balancing Services Volume Data as part of their imbalance reporting, allowing for a service specific optimisation as the main supplier will no longer be penalised for a volume disparity in their allocation due to LCM delivery. This change applies for smaller non-BM units such as the SLIQ prototype.

Demand Flexibility Service

The NESO introduced the Demand Flexibility Service (DFS) during the winter of 2022/23, and have run trials to develop the service across two winters since then. The purpose of the DFS is to help NESO to maintain secure operation of the electricity system by incentivizing both domestic and commercial energy users to reduce or shifting their demand in response to notification of DFS events.

StorTera could provide the DFS with the SLIQ installation at StorTera HQ either through their appointed electricity supplier (if they are a registered DFS provider) or through an aggregator or another third party.

Arbitrage

In addition to the flexibility services through SPEN and NESO, the SLIQ can be used to charge at low demand periods and discharge at peak demand periods, a process known as arbitrage. This can benefit the wider network by reducing peak demand, and also benefit StorTera if there is a sufficient price differential (known as arbitrage spread) between the import and export electricity prices paid. The largest benefit is likely to be with an import contract and PPA linked to day-ahead electricity market prices to take full advantage of the flexibility offered by the SLIQ. StorTera have held discussions with an energy supplier who could offer contracts based on day-ahead market prices, however a subsequent change to the supplier's policies introduced a minimum annual threshold of 1GWh which StorTera could not meet with the HQ site alone. For the demonstrator project, a simpler import contract and export PPA with either single or set time banded pricing may be preferable to give certainty of costs and time windows for charging and discharging the batteries for testing, and could later be changed to a dynamic tariff for optimisation.

Carbon lifecycle

Introduction

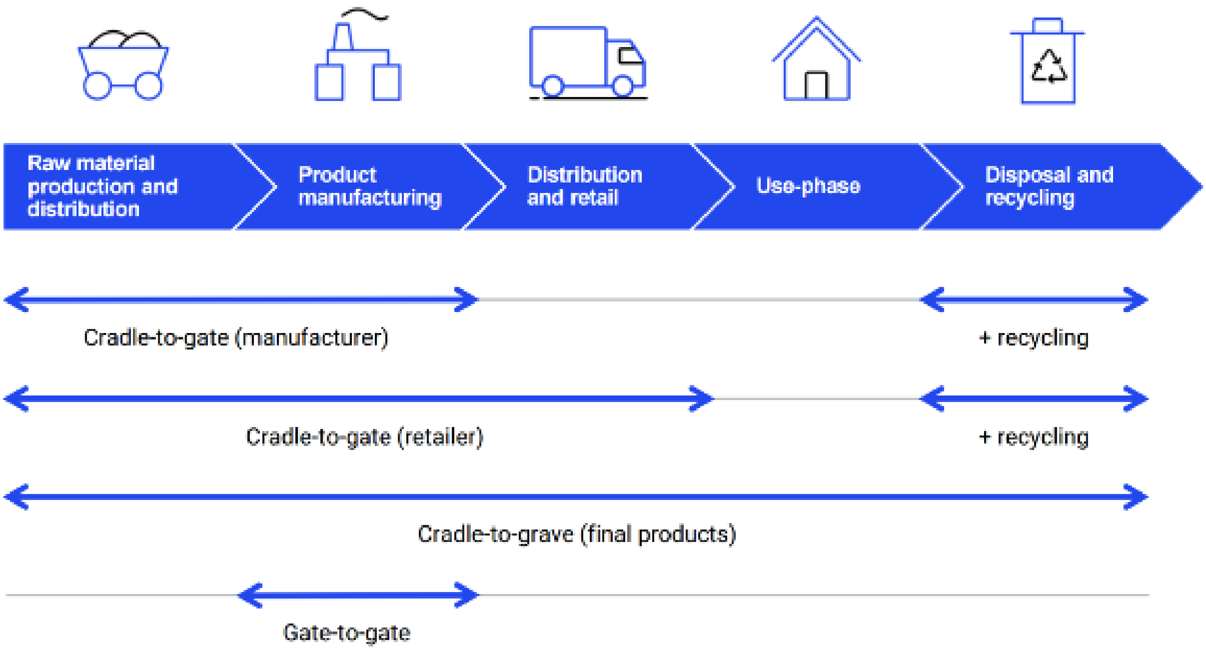
A Carbon Lifecycle Assessment (LCA) analyses the entire life cycle of a product or service including all relevant phases such as extraction of raw materials, transportation, manufacturing processes and disposal. A lifecycle assessment at a product level is referred to as product carbon foot printing (PCF) as the focus is placed on the greenhouse gas emissions generated.

A carbon footprint is the total greenhouse gas emission (GHG) caused directly and indirectly by an individual, organisation, event or product, and is expressed as a carbon dioxide equivalent (CO2e). Greenhouse gases include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2) and many others including gases such as refrigerants e.g. HFCs, PFCs, SF6.

The LCA for the SLIQ was completed following internal training and reading and with the support of Carbon Trust. The Carbon Trust is a world leader in carbon footprint and labelling, having been instrumental in developing the world's first product carbon footprinting standard PAS2050. StorTera carried out research in order to identify the best approach to assessing the carbon footprint of the SLIQ, arranged external support and advice and compiled the detailed bill of materials required to carry out the assessment.

The assessment includes a cradle to gate assessment which considers raw materials and manufacturing of the product and cradle to grave which includes the use/operational phase (Figure 6).

Figure 6: Graphic showing different phases assessed in LCA



Assessment results

Emissions breakdown

Scope 3 emissions were considered to form the majority of the total value chain footprint of the SLIQ with the breakdown of emissions as follows:

- Production 12%
- Transportation 1%
- Use phase 87%
- End of life <0.1%

The worst-case scenario assumed the SLIQ is charged only with power from the UK grid rather than from onsite renewable generation. Use phase emissions also consider waste electricity during charging and discharging cycles i.e. losses due to <100% efficiency.

A total of 377.7 tonnes CO2e/lifetime is expected with the majority being estimated to be in the use phase as waste electricity during charging and discharging cycles. This works out to be between 36 and 283 gCO2e/kWh with the variation being the difference between on-site generation from renewables (lower end) being used to charge the SLIQ and UK grid (higher end).

Production Emissions

Emission during the production phase are driven mostly by the use of lithium in both catholyte and spiral cells as well as steel in the PCS module, module enclosure, PLC and control electronics and a small amount in the flow system in safety release valves and pressure sensors.

Transportation emissions

Transportation emissions were calculated using common cargo routes and BEIS 2024 freight emission factors. 17 tonne payloads were assumed with single deliveries and short distances keeping emissions low. Being manufactured in the UK, transportation is a minor contributor (1%) to the lifetime emissions at 3.7 t CO_2e.

Use-Phase Emissions

Use-Phase Emissions were calculated using the EU grid emission factor (IEA 2024) and assuming 20,000 cycle life, 90% round trip efficiency and 5% linear capacity fade over lifetime. A total of 515.3t CO_2e was calculated with 4t being contributed to maintenance and 511t attributed to wastage due to <100% efficiency.

End of Life Emissions

End of life emissions were calculated to be minimal at 0.025t CO_2e (<0.1% of lifetime emissions). This is mainly due to the majority of raw materials being easily recyclable and assuming 70% recycled content for steel in the SLIQ.

Results and conclusions

The worst-case scenario calculates the cradle to grave emissions to be 377.7 t CO_2e per SLIQ battery lifetime which works out to be 283 gCO_2e/kWh. For comparison, a combined cycle gas turbine (CCGT) is ~488 gCO_2e/kWh[i].

In reality, the SLIQ is likely to be charged with on-site renewable energy generation rather than grid power since the business case is significantly better when renewable energy is being optimised, for example avoiding curtailed wind, storing excess renewables and using it to offset peak demand.

The carbon footprint of the SLIQ was calculated to be 36 gCO_2e/kWh when onsite renewable generation is used to charge the battery which is significantly lower than grid charging and compared to CCGT. It is also lower than the carbon footprint of solar which is calculated to range from 45 to 90 gCO_2e/kWh1. The carbon footprint calculation assumed an efficiency of 90% whereas tests have shown that the SLIQ is 94-95% efficient which will reduce the use phase emissions further.

Overall, this study has been a good starting point to monitor and improve the SLIQs carbon footprint as it moves closer to commercialisation. It will be essential for inclusion in the EU Battery Passport, a tool for reporting key data like carbon footprint, material composition and recycling information, which will become a legal requirement in 2027[ii]. The Carbon Border

Adjustment Mechanism (CBAM) will also demand carbon footprint information of goods to enable the EU to put a fair price on carbon emitted during the production of carbon intensive goods that are entering the EU[iii].

Sustainable supply chain

Introduction

As part of planning for commercialisation, StorTera undertook work to start to identify and build a supply chain for the SLIQ that minimises the negative impact that the product has on the 3 pillars of sustainability namely; social, economic and environmental.

Taking the SLIQ and applying it to all 3 pillars results in the following observations:

- Social – The SLIQ will not harm human health, no society or individual is harmed or detrimentally affected in any way via the SLIQ.
- Economic – The SLIQs profitability to StorTera allows the company to continue operating. The SLIQ itself is affordable and slots into the energy generation system, otherwise it will not be competitive. StorTera will create jobs from it too.
- Environmental – The SLIQ does not negatively impact water or air quality. It is made of natural resources at a rate which allows them to be regenerated or re-used.

The comments above include the SLIQ product itself, as well as its production (including the materials of construction and their impact) and its impact at the end of life. Therefore, the components that make the SLIQ unique must fit into the above criteria.

In Phase 1, we carried out research into how we could ensure the SLIQ supply chain is sustainable and developed some tools which could be used to assess suppliers. In Phase 2, we built on this work by improving and integrating the sustainable supply chain tools into our internal procedures. We have also considered where more sustainable sources of raw materials for the SLIQ exist and how we can acquire these in future as well as ways we can reduce the amount of critical raw materials (CRM) in the supply chain.

Market entry

Introduction

StorTera's vision is to develop and commercialise the SLIQ as a low cost, highly efficient and sustainable energy storage technology. To achieve this, it is critical to ensure that the end product can be cost-effectively manufactured at scale, and this requirement must be considered from early on in the design process. To develop this highly innovative, first of a kind complex technology, StorTera engaged with a variety of stakeholders with specific expertise to obtain expert advice and identify possible design and process changes to ensure suitability for manufacturing. Stakeholders include suppliers, subcontractors, and consultants for different components of the SLIQ.

Market role

A 'SLIQ technical review' was undertaken by a consultant as part of the NZIP support programme. As well as reviewing the technology and recommending a route to certification, they assessed the market roles that StorTera can choose to take when commercialising the SLIQ. The table below summarises the market roles for StorTera's technology.

Table 2: Market roles for the SLiQ

Role	Description of role
Site operator	The site operator is responsible for monitoring the site for the purposes of safety, security and damage to the site, and ensuring the services are delivered to the offtake or the energy supplier (under a tolling agreement). This includes responsibility for scheduled maintenance, post-fault investigations, assessing performance against the assumptions in the financial model and performance optimisation. The site operator may provide these services for many sites, in which case the term "asset manager" is often used. The project developer often plays this role. Even in the case of an investor acquiring 100% of the shares in the Special Purpose Vehicle, the project developer may be retained as the Site operator by means of a services contract to the Special Purpose Vehicle. The Site Operator may rely on sub-contracts for specific items (such as site security). It will oversee ongoing duties from the Original Equipment Manufacturer (OEM) with respect to inspection, maintenance, warranties, post-fault investigation and replacement of failed parts

Technology provider	The technology provider manufactures or licenses a core item of technology required by the Original Equipment Manufacturer (OEM) to manufacturer a marketable product at the scale required for grid-scale storage or EV charging hubs. In some cases, the Original Equipment Manufacturer is also the technology provider (or has secured the technology through acquisition). By contrast, the technology provider either has elected not to provide, or does not have the capacity to provide, a full marketable product at the scale required for grid-scale storage
Original Equipment Manufacturer (OEM)	The OEM manufactures and sells a marketable product at the scale required for grid-scale storage or EV charging hubs. The OEM leads marketing efforts to project developers, and technology qualification efforts with project developers. It has secured product safety and electromagnetic compatibility certificates as necessary. It requires no further development, and the minimum of specification, by the project developer. The OEM provides warranties for performance of the equipment, including wrapping and taking responsibility for any underlying warranties it has secured with technology providers. It has secured manufacturing capacity and contracts with raw materials suppliers. In some cases, the OEM is also the technology provider (or has secured the technology through acquisition). In some cases, the OEM also provides an EPC service.
Engineer, Procure, Contract (EPC) contractor	The EPC provides a turn-key design, procure, install and commission service to the renewable developer. It takes as its inputs the permits and their associated conditions, the grid connection agreement and its requirements, an Employer's Requirements issued by the project developer specifying the minimum performance requirements of the grid-scale storage or EV charging hub, and a shortlist of qualified OEMs. It runs procurement for ancillary, non-specialist equipment.
System integrator	A system integrator coordinates the design of separate OEMs' systems at a site. It designs, specifies and configures control systems, leads Functional (or Factory) Acceptance Tests, oversees installation and System Acceptance Tests. It does not wrap or take responsibility for the warranties from the OEMs. It typically excludes aspects offered by an EPC (such as ground investigations, enabling works and civil works) and is may not hold accreditation for Low Voltage (IET 18th Edition Wiring Regulations) or High Voltage works

Project Developer	This is the entity which conceives of the project at the outset; carries out site-finding activities, secures essential permits, and secures grid connections and/or modifications to a site owner's existing grid connection. It develops a financial model, selects and qualifies the storage technology. It markets the project for financing (save for where the project is financed from its own balance sheet). The role is also occasionally referred to as the project "Sponsor". The project developer may rely on one or more subcontractors to execute these activities. Frequently the project developer will establish and structure its relations with planning authorities, off takers, energy suppliers and statutory undertakers (such as transmission and distribution connections) through a "Special Purpose Vehicle (SPV)" to facilitate project financing, in which the lenders will have no recourse to the project developer as the parent company. The SPV may also be referred to as the "Project Company".

The report also summarised the design detail, assurances and certifications sought by project participants which is extremely helpful to StorTera to prepare for commercialisation, as shown in the table below.

Table 3: Design detail, assurance or certifications required for commercialisation

Design detail, assurance or certification	Description	Actors who may require this, and for what purposes
Technology qualification	Early stage, third party review of the technology according to a recognised framework such as DNV-RP-A2031. It is particularly appropriate for new technologies where pre-existing standards and rules are incomplete.	Project developer when carrying out technology selection for an application or project. OEM when negotiating a licencing arrangement with a technology provider

Chemical content at cell level	Detail of chemicals used in the manufacturing process and the risk of exposure to both human and animal life.	OEM when negotiating a licencing arrangement with a technology provider. Project developer when carrying out technology selection for an application or project. Project developer when carrying out an Environmental Impact Screening Assessment (EISA) or preparing a planning application.
Degradation curve Capacity degradation curve	Curves of cell degradation in an industry-recognised format (e.g., in accordance with IEEE 1679-2020). Curves of capacity degradation, after any redundancy and fail-safes provided by a Battery Management System, in an industry-recognised format (e.g., in accordance with IEEE 1679-2020).	Project developer when preparing a commercial bid. OEM when negotiating a licencing arrangement with a technology provider. OEM when preparing a tender response for battery main equipment supply. EPC when preparing a response which wraps battery main equipment supply. Site operator when analysing and optimising site operation and when checking compliance with the Long-Term Service Arrangement (LTSA) and its requirements on capacity

Depth of discharge	Limitations on depth of discharge stated in an industry-recognised format (e.g., in accordance with IEEE 1679-2020).	Project developer when preparing a commercial bid. OEM when negotiating a licencing arrangement with a technology provider. OEM when preparing a tender response for battery main equipment supply. EPC when preparing a response which wraps battery main equipment supply or carrying out Front End Engineering Design (FEED)
Certifications at cell, tray, rack and container level	UL 1973, UK9540, IEC 62495-2, IEC 61501 and 61511 (requirements for a fail-safe design of internal controls), IEC 62619, NFPA 855.	Project developer at tender stage for EPC and/or battery main equipment supply. EPC when preparing a response which wraps battery supply. In mature markets (e.g., solar PV and wind) it is known for project developers to submit commercial offers (e.g. into an ancillary services auction) and accept EPC offers, on the condition that remaining certifications are in place as a condition subsequent, or by a defined date prior to Commercial Operation Date
UKCA / CE marking and compliance with Low Voltage Directive	Certification that all user-facing equipment is compliant with low voltage and EMC requirements, including, for example, Battery Management System.	Project developer at tender stage for EPC and/or battery main equipment supply. EPC when preparing a response which wraps battery supply. Site operator when preparing to take over the site

Fire test	A fire test at rack level (in accordance with UK-9540A) is typically carried out to inform fire spread calculations. Fire spread calculations evaluate the danger to neighbouring facilities and equipment in the worst case in which a fire has started, notwithstanding the preventive measures designed in. The results of the first test act as the combustion source in the fire spread calculation. The fire test results can also be used to inform plume analysis, designed to demonstrated that particulate matter spread in the plume of a fire is within tolerable limits at neighbouring receptors.	Project developer when carry out plume analysis at planning & consenting stage. EPC when carrying out Front-end Engineering Design, either to inform its tender response, or having been appointed as preferred supplier. Project developer or site operator when agreeing firefighting procedures with the local fire authority
Procedure for disposal and recycling of cells	Procedure and assurance of complying with disposal and recycling regulations (such as The Batteries and Accumulators (Placing on the Market) Regulations 2008, as amended, and Waste Electrical and Electronic Equipment Regulations)	Project developer when finalising selection and contract with battery main equipment supplier or EPC.
Safe system of work	A safe system of work at rack and tray level, covering both electrical and manual handling considerations. It should consider points of electrical isolation, safe discharge, and supply of any additional specialist tools.	EPC and site operator when carrying out Hazard and Operability Study

ISO9001, 14001, 180001	Evidence of quality, environmental and health & safety management procedures.	Project developer at tender stage for EPC and/or battery main equipment supply. EPC when preparing a response which wraps battery supply
Fleet defects management process / safety notification process	Assurance that the battery main supplier has robust systems with which it is tracking defects across its fleet of shipped products and is notifying other customers of any fleet defects which affect their sites.	Project developer at tender stage for EPC and/or battery main equipment supply. EPC when preparing a response which wraps battery supply. Site operator when entering the LTSA period after the Commercial Operation Date (COD)

Conclusion

This report has summarised the work carried out under the project titled ‘Sustainable Single Liquid Flow Battery’ during which StorTera have delivered a first-of-a-kind LoDES demonstrator using our innovative SLiQ technology that is based on lithium polysulphide chemistry. The system is installed in a local micro-grid that allows all of the sub-systems and functionality to be rigorously tested in a real environment.

Significant technical progress has been made in each key SLIQ innovation area including cell, pack, system, catholyte and balance of plant.

The SLiQ demonstrator system has met all of the performance requirements of the competition as follows:

- Long 10-hour discharge duration
- Minimal self-discharge of 0.02% over 4-hour storage periods during normal operation
- High round trip efficiency of 91% (DC coulombic)
- Minimal long term self-discharge rate of <0.1% catholyte charge loss when catholyte is stored separately to the cells
- High charge rate of 0.33C (fully charged in 3 hours)

Throughout the project, lessons for scaling have been captured to enable StorTera to identify a clear path to commercialisation and scale up. The next steps include reducing system costs in order to make the SLIQ competitive in the market and improving manufacturability and supply chain to ensure successful scale up of the technology.

Figure 7:The SLiQ demonstrator

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