IMPERIAL COLLEGE LONDON

Faculty of Natural Sciences

Centre for Environmental Policy

Investigating the investment and operational costs of the Na-Zn molten salt battery and evaluating how cost competitive it will be against other technologies in the future.

By

Ross Berridge

A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC.

08 September 2021

Declaration of Own Work

I declare that this thesis

Investigating the investment and operational costs of the Na-Zn molten salt battery and evaluating how cost competitive it will be against other technologies in the future.

is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

Signature: R Berridge

Name of student: Ross Berridge

Name of supervisors: Dr Iain Staffell and Dr Oliver Schmidt

Funding Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 963599.

Authorisation to Hold Electronic Copy of MSc Thesis

Thesis title: Investigating the investment and operational costs of the Na-Zn molten salt battery and evaluating how cost competitive it will be against other technologies in the future.

Author: Ross Berridge

I hereby assign to Imperial College London, Centre of Environmental Policy the right to hold an electronic copy of the thesis identified above and any supplemental tables, illustrations, appendices, or other information submitted therewith (the "thesis") in all forms and media, effective when and if the thesis is accepted by the College. This authorisation includes the right to adapt the presentation of the thesis abstract for use in conjunction with computer systems and programs, including reproduction or publication in machine-readable form and incorporation in electronic retrieval systems. Access to the thesis will be limited to ET MSc teaching staff and students and this can be extended to other College staff and students by permission of the ET MSc Course Directors/Examiners Board.

Signed: R Berridge

Name: Ross Berridge

Date: 08 September 2020

Abstract

Due to the rise of intermittent renewables within the energy mix to combat climate change, there is a growing demand for grid-scale energy storage to maintain grid reliability and flexibility. Battery energy storage systems (BESS) are the most suitable option for grid-scale energy storage, but current BESS have limitations that have restricted their mass adoption. Due to these limitations, the SOLSTICE project was created to develop the Sodium-Zinc (Na-Zn) molten salt battery that aims to meet the demand for a low-cost, grid-scale, energy storage system required to facilitate the transition towards a net-zero energy system.

However, to this date, there has been relatively few cost estimates for the Na-Zn battery, and no cost estimates using a bottom-up approach. This study bridges this gap by using primary and secondary data from published literature and expert elicitation coupled with a bottom-up engineering cost model to estimate the cost of the solid-electrolyte Na-Zn battery concept. Subsequently, its cost competitiveness against other energy storage technologies in the future will be examined.

Through the compilation of data on the Na-Zn battery's design, electrochemistry, assembly, and material composition the bottom-up model outputs a total solid-electrolyte battery system cost per kWh of \$116.60 ±22.6% and cycle cost (\$/kWh/cycle) of \$0.023 ±34.8%. By comparing the Na-Zn battery cost per kWh with projected costs of alternative energy storage technologies from published literature, this study suggests the Na-Zn solid electrolyte battery will be the most cost-competitive grid-scale storage option at the time of its commercialisation in 2030. Furthermore, as the calculated Na-Zn battery cycle cost \$0.023 ±34.8% is below the EU Strategic Energy Technology (SET) plan target of <0.06 \$/kWh/cycle, this study proposes the Na-Zn battery is a viable technology to facilitate the transition to a climate-neutral EU energy system.

Acknowledgements

I would like to thank my supervisors Dr Iain Staffell and Dr Oliver Schmidt for the opportunity to take part in such an interesting and rewarding project regarding Na-Zn batteries. Thank you for your advice and feedback, which have been instrumental in the creation of this thesis.

I would also like to thank the members of the SOLSTICE consortium for giving their time for interviews and providing invaluable information to aid this study.

Table of Contents

Ethics Declaration

I declare that this thesis

Investigating the investment and operational costs of Na-Zn molten salt batteries and evaluating how cost competitive they will be against other technologies in the future.

was granted ethics approval on 04/06/2021 by Mark Burgman, Head of Department, and Mike Tennant, the CEP Approver under delegated authority of RGIT under the reference number CEPREP-2021-05-141.

Signature: R Berridge

Name of student: Ross Berridge

Name of supervisor: Dr Iain Staffell and Dr Oliver Schmidt

List of Figures

List of Tables

List of Abbreviations

kWh	Kilowatt-hour
BESS	Battery Energy Storage Systems
LMB	Liquid Metal Battery
MSB	Molten Salt Battery
R&D	Research and Development
Ah/kg	Ampere-hour per kilogram
Wh/kg	Watt-hour per kilogram
MSB	Molten Salt Battery
BatPaC	Battery Performance and Cost model
ZEBRA	Sodium-nickel chloride battery
BoS	Balance of System
Na-Zn	Sodium-Zinc
Ni-Cd	Nickel-Cadmium
Na-S	Sodium-Sulphur
Li-ion	Lithium ion
Ni-MH	Nickel Metal Hydride
NaNiCl	Sodium Nickel Chloride
sf	Significant figures
dp	Decimal places

Executive Summary

Investigating the investment and operational costs of Na-Zn molten salt batteries and evaluating how cost competitive they will be against other technologies in the future.

Imperial College London - Centre for Environmental Policy
Ross Berridge, MSc Thesis (Academic Year 2020/2021)
Supervisors: Dr Iain Staffell and Dr Oliver Schmidt

Objectives

The paper aims to build a bottom-up cost-engineering model that estimates the overall cost of the solid electrolyte Na-Zn battery system through the collection of relevant primary and secondary data from published literature and expert elicitations. The objectives to achieve this aim are to (1) assess the role of different materials, components, electrochemical characteristics and assembly in affecting the total Na-Zn solid electrolyte battery cost, (2) to determine the main cost drivers and evaluate the areas with the greatest potential for cost reductions, and (3) to evaluate the cost competitiveness of the solid-electrolyte concept compared to projected costs of competing energy storage technologies at the time of the Na-Zn battery's proposed commercialisation in 2030.

Introduction

Due to the rise of intermittent renewables within the energy mix to combat climate change, there is a growing demand for grid-scale energy storage to maintain grid reliability and flexibility. Battery energy storage systems (BESS) are the most suitable energy storage option, but current BESS have limitations that have restricted their mass adoption. Due to these limitations, the SOLSTICE project was created to develop the Sodium-Zinc (Na-Zn) molten salt battery that aims to meet the demand for a low-cost, grid-scale, energy storage system required to facilitate the transition towards a net-zero energy system.

However, to this date, there has been relatively few cost estimates of Na-Zn batteries, and no cost estimates using a bottom-up approach. This study bridges this gap by using primary and secondary data from published literature and expert elicitation coupled with a bottom-up engineering cost model to estimate the cost of the solid-electrolyte Na-Zn battery concept. Subsequently, its cost competitiveness against other energy storage technologies in the future will be examined.

Methodology

This study uses a bottom-up approach that collects relevant secondary data from desk research and primary data collected through expert elicitations with members of the SOLSTICE consortium to use as input parameters in a bottom-up engineering cost model. This model then estimates the total battery system cost of the novel Na-Zn solid electrolyte molten salt battery.

The bottom-up model used for this paper was created in Microsoft Excel and consisted of three spreadsheets working in conjunction. The first spreadsheet, the input sheet, was where the primary and secondary data collected during desk research and expert elicitations were logged. This consisted of input parameters on relevant battery design details such as volumes and thicknesses, battery component material costs and dimensions, and various electrochemical characteristics of the Na-Zn battery such as the theoretical electric potential and current. The second spreadsheet was the calculation sheet where the input parameters were synthesised to calculate any useful outputs. These include the mass and volume of active materials, the electric potential and energy per cell, the battery components mass and material cost, and the assembly and energy costs. These calculations were then combined to calculate the total Na-Zn battery system costs. Finally, the output sheet highlighted the most important outputs from the calculation sheet. This included the cost per cell, cost per battery (assuming an 18.4 kWh battery consisting of 240 cells) and cost per kWh of all the individual cell components, Balance of System (BoS), components, assembly, energy, and the total battery system. The total battery system cycle cost was also calculated and shown.

The Monte Carlo method was used on the bottom-up cost model to assess the uncertainty in the total cost estimates by automating the input parameter space within their attributed range of uncertainty based on a review of published literature and expert elicitations. Once the mean and range of the uncertainty for each input parameter had been determined, the Monte Carlo method was carried out by generating 1000 values for each input parameter assuming a normal distribution centred around the mean with a standard deviation of 0.1 and a cut off at the upper and lower range limits. These values were then input into an excel spreadsheet and used to generate 1000 total costs that presented the uncertainty in the total cost estimates.

Results

The bottom-up model generated a total cost per cell ($/cell) value of $8.77, a total cost per battery ($/battery) of $2105.27, a total cost per kWh ($/kWh) of $114.15, as well as a total cycle cost ($/kWh/cycle) of $0.025.

A pie chart displaying the percentage cost breakdown of the total Na-Zn solid electrolyte system cost can be seen in Figure 1, where the main cost contributors are the cost of the cell components, the battery assembly cost, and the cell assembly cost occupying 41.4%, 19.9% and 17.6% of the total battery system cost per kWh respectively.

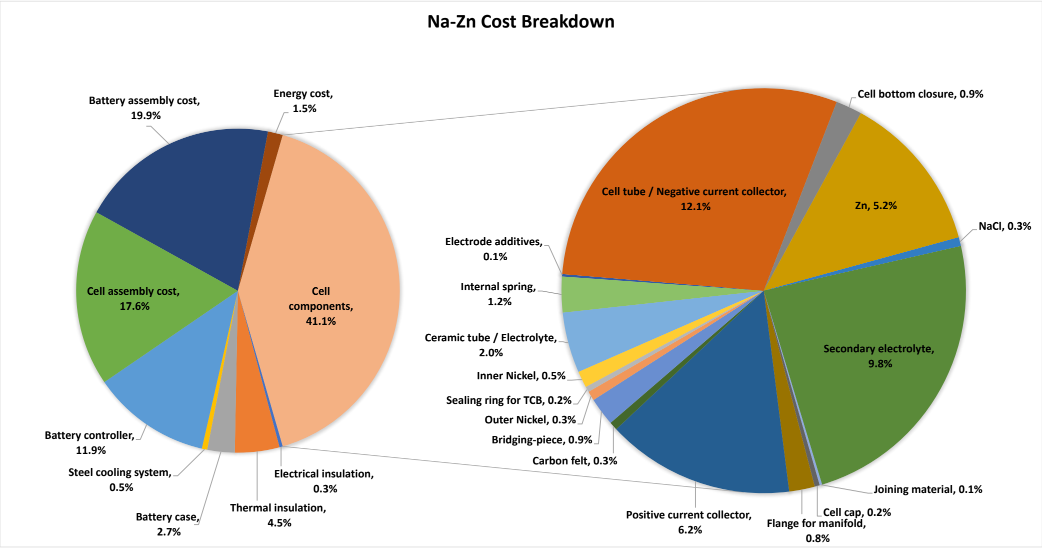
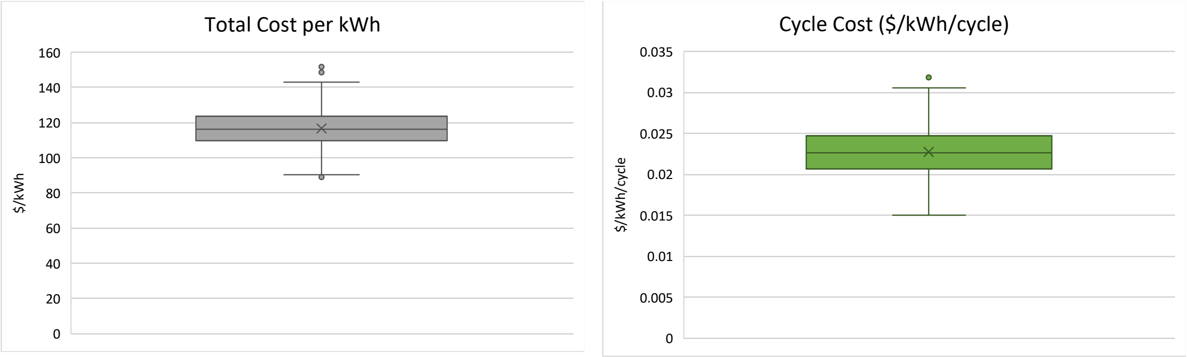


Figure 1: Pie chart showing the percentage cost breakdown of the Na-Zn solid electrolyte battery system.

After the Monte Carlo method was applied a range of total cost values were generated displaying the uncertainty in the total cost values based on the uncertainties attributed to certain input parameters. The range of results produced by the Monte Carlo analysis for the cost per kWh ($/kWh) as well as the total cycle cost ($/kWh/cycle) can be seen in Figure 2.

As seen in Figure 2a the total cost per kWh ranged from a low of $90.45 to a high of $143.15 with a mean of $116.60, giving a cost value with percentage uncertainty of $116.60 ±22.6%.

In Figure 2b the cycle cost ranges from a low of $0.015 to a high of $0.031 with a mean of $0.023, giving a cycle cost value with percentage uncertainty of $0.023 ±34.8%.



(a) (b)

Figure 2: Box and whiskers plots displaying the uncertainty in the total cost values generated using the Monte Carlo method on the bottom-up cost model. (a) displays the range of results for total cost per kWh. (b) displays the range of results for the total cycle cost. Outlier values have been highlighted as dots outside of the error bars.

To assess how uncertainties in various model parameters affected the total cost per kWh a sensitivity analysis was performed. The parameters that caused the greatest sensitivity in the total cost per kWh are uncertainties in the theoretical electric potential (causing sensitivity in the total cost per kWh ranging from $103.79 to $126.86 with a total spread of $23.07), the cell assembly percentage of the total cost (causing the total cost to range between $105.78 and $125.31 with a total spread of $19.53), the battery assembly percentage of the total cost (causing the total cost to range between $106.57 and $125.52 with a total spread of $18.95), and the secondary electrolyte percentage of cathodic volume (causing the total cost to range between $108.82 and $122.15 with a total spread of $13.33).

Discussion, Conclusions, and Implications

By comparing the Na-Zn battery cost per kWh of $116.60 ±22.6% with projected costs of alternative energy storage technologies from published literature, this study suggests the Na-Zn solid electrolyte battery will be the most cost-competitive grid-scale storage option at the time of its commercialisation in 2030. Furthermore, as the calculated Na-Zn battery cycle cost of $0.023 ±34.8% is below the EU Strategic Energy Technology (SET) plan target of <0.06 $/kWh/cycle, this study proposes the Na-Zn battery is a viable technology to facilitate the transition to a climate-neutral EU energy system.

However, the projected costs of alternative storage technologies also show that the electrolysis price is forecast to drop to ≈$100 per kWh by 2040, thus outcompeting the Na-Zn battery in terms of cost. This means additional cost reductions to the Na-Zn battery system would be necessary to stay cost-competitive.

The main areas for potential cost reductions within the Na-Zn battery system are highlighted in the cost breakdown (Figure 1) and sensitivity analysis. One possible solution to reduce costs is economies of scale. This would cause cost reductions through reduced material cost when bought at a large scale and lower assembly costs through a larger and more automated production process.

The biggest cost contributor was the cost of the cell components, and within the cell components the biggest cost contributors were the cell tube and molten NaAlCl4 secondary electrolyte. These large costs came from the component's expensive material cost of ≈$13.2/kg for the cell tube, and ≈$7/kg for the $NaAlCl_4$, combined with a large volume per cell for each component. From the sensitivity analysis, it was evident that for the cell tube the greatest potential cost reduction could be achieved by replacing the costly nickel-plated steel with a relatively cheaper material, whereas for the secondary electrolyte the greatest cost reduction potential comes from reducing the percentage volume of NaAlCl4 in the cathode.

As seen in Figure 1 the next largest battery system cost contributors are the battery and cell assembly costs. This is further supported in the sensitivity analysis where the cell assembly percentage of the total cost (causing the total cost to range between $105.78 and $125.31 with a total spread of $19.53), and the battery assembly percentage of the total cost (causing the total cost to range between $106.57 and $125.52 with a total spread of $18.95) cause the second and third greatest sensitivity in the total cost per kWh respectively. A potential cost reduction in the assembly process could be achieved through automatization of the assembly process and utilization of advanced machinery capable of dealing with a large supply of material.

There are many limitations to the bottom-up model that impacted the cost estimates of the Na-Zn solid electrolyte battery:
Firstly, due to the limited primary and secondary data available for the novel Na-Zn battery technology, there were limitations in the accuracy of the input parameters, including limitations in the battery design, dimensions, assembly, electrochemical characteristics, and material cost. Because of these limitations, this study assumes most of the cell components have the same material composition and mass as the ZEBRA battery.

Further limitations occur due to the confidentiality of information. During expert elicitations, it was a common occurrence that important information for the model was confidential due to companies' interests. This impacted the accuracy of the model's cost estimates as assumptions had to be made where primary data could not be collected.

Finally, there were limitations in the model's BoS, assembly and energy cost estimates as these were not calculated through a bottom-up approach and instead obtained from primary and secondary data.

To build on this model future studies should calculate the Na-Zn battery assembly, BoS, and energy costs through a bottom-up approach, perform a learning curve analysis to project future battery system costs, and conduct a similar bottom-up cost model on the all-liquid Na-Zn battery concept.

1.0 Introduction

1.1 Background

In 2015, the Paris Agreement was initiated to tackle global warming by limiting the global temperature rise to below 2°C above pre-industrial levels (Savaresi, 2016). To achieve this goal, it is crucial to decrease reliance on fossil fuels and increase the deployment of renewable energy sources such as solar and wind (Cash, 2018). Progress in deployment can already be seen, and it is expected that renewables will supply up to one-third of the world's electricity by 2025, overtaking coal as the largest global source of electricity (IEA, 2020).

However, these renewables are intermittent with their power output varying depending on the time of day and weather conditions (Chen et al., 2020). Integration of energy storage systems with renewables is one of the key options to maintain grid reliability and flexibility in a renewable dependent electricity grid by balancing out this intermittency (Chen et al., 2020). Energy storage systems can provide this by capturing excess energy and storing it to be used later when it is needed within the electrical power grid (Chen et al., 2009).

Currently, the most dominant forms of energy storage are: Pumped hydropower, occupying more than 98% of the worlds bulk storage capacity (Tsiropoulos I, Tarvydas D & Lebedeva N, 2018); Hydrogen, with hydrogen electrolysers and fuel cells making up 7.5-12 GW (Few, Schmidt & Gambhir, 2016); and Lithium-ion batteries, the most widely used battery storage option, controlling more than 90% of the current global grid battery storage market (Laporte, 2019).

However, all these energy storage options have limitations associated with them (See Table 1). Therefore, there is a demand for research & development (R&D) into new technologies that combat these limitations. Sodium-Zinc (Na-Zn) molten salt batteries are a novel battery storage technology that aims to meet the demand for a low-cost, large-scale, energy storage system required to facilitate the transition towards a net-zero energy system heavily reliant on intermittent solar and wind power.

Table 1: Limitations to Pumped hydropower, Hydrogen and Lithium-ion batteries.

Technology	Limitations	Source
Pumped hydropower	- Large unit size - Site specific - Slow response times (>10s) - Long construction times	(Barbour et al., 2016; Schmidt et al., 2019)
Hydrogen	- High capital cost (~$4000/kWh) - Slow response time - Relatively low efficiency - Low life expectancy	(Ibrahim, Ilinca & Perron, 2008; Iwasaki, 2003)
Lithium-ion	- Material bottleneck concerns (lithium and cobalt) - Relatively high initial cost (~$200/kWh) - Unsustainable mining - Not easily recyclable -Risk of thermal runaway and explosions	(Dufo-López *et al.*, 2018; Few, Schmidt & Gambhir, 2016; Kubiak *et al.*, 2017)

1.2 Aims and Objectives

However, there has been little research conducted into this novel battery technology, and it is not known how much Na-Zn batteries will cost. This study aims to bridge this gap and investigate the investment and operational costs of the Na-Zn solid electrolyte battery concept. Through the collection of relevant primary and secondary data from published literature and expert elicitations, a bottom-up cost-engineering model will be built to estimate the overall solid electrolyte Na-Zn battery system cost.

The objectives to achieve this aim are to (1) assess the role of different materials, components, electrochemical characteristics and assembly in affecting the total Na-Zn solid electrolyte battery cost, (2) to determine the main cost drivers and evaluate the areas with the greatest potential for cost reductions, and (3) to evaluate the cost competitiveness of the solid-electrolyte concept compared to projected costs of competing energy storage technologies at the time of the Na-Zn battery's proposed commercialisation in 2030. (1) is addressed in chapters 3.5, 3.6, 3.7, 4.2 and 4.4. (2) is addressed in chapters 4.2, 4.32, 4.4, and 5.2. (3) is addressed in chapter 5.1.

Finally, this study recognises limitations associated with the model and proposes improvements to refine the bottom-up model and its cost estimations, as well as outlining the further data required and the necessary next steps to expand the cost investigation to the all-liquid electrolyte Na-Zn battery concept.

2.0 Literature Review

2.1 Battery Energy Storage Systems

Electrical energy storage is one of the key options to cope with the increased reliance on intermittent renewables (Chen et al., 2020). For grid-scale electrical energy storage, battery energy storage systems (BESS) are the most suitable energy storage option with attractive features such as a rapid response time, location flexibility, modularization, high efficiencies, and relatively short construction cycles (Fan et al., 2020a; Zhao, Ding & Wen, 2019).

Many battery technologies have been developed to meet the increasing demand for a grid-scale electrical energy storage solution, including lead-acid batteries, Ni-Cd batteries, Ni–MH batteries, Na–S batteries, Li-ion batteries, and redox flow batteries (Zhang *et al.*, 2018). All these technologies have advantageous characteristics for large-scale energy storage but also have limitations that have restricted their mass adoption and encouraged R&D into alternative BESS technologies summarised in Table 2 (Fan et al., 2020a; Zhang et al., 2018).

Table 2: Limitations of different types of battery energy storage systems.

Technology	Limitations	Source
Lead Acid Battery	- Limited energy density (30-50 Wh/kg) - Environmental pollution - High self-discharge - Relatively short cycle life (500-1000 cycles)	(Fan et al., 2020a; Zhang et al., 2018).
Ni-Cd Battery	- Limited energy density (50-75 Wh/kg) - Relatively high cost (~$1000/kWh) - Contains toxic Cadmium - Contains corrosive alkaline electrolyte	(Zhang *et al.*, 2018).

Ni-Mh Battery	- Relatively high cost (~$300/kWh) - Decreased performance at low temperatures	(Zhang *et al.*, 2018; Cheng Yang *et al.*, 2017).
Na-S Battery	- High operating temperature (>300°C) - Relatively high cost ($350/kWh) - Safety concerns	(Fan et al., 2020a; Zhang et al., 2018).
Li-Ion Battery	Material bottleneck concerns (lithium and cobalt) - Relatively high initial cost (~$200/kWh) - Unsustainable mining - Not easily recyclable -Risk of thermal runaway and explosions	(Dufo-López *et al.*, 2018; Few, Schmidt & Gambhir, 2016; Kubiak *et al.*, 2017)
Redox-Flow Battery	- Relatively high cost ($380/kWh) - Requirement of large space - Relatively low energy density (10-50 Wh/kg)	(Fan *et al.*, 2020; Zhang *et al.*, 2018, 2012)
Zebra Battery	- Uses costly nickel - High operating temperatures (265-350°C)	(van Zyl, 1996; Shamim *et al.*, 2021)

2.2 Molten Salt Batteries

Molten salt batteries (MSBs) are a class of battery that operate at high temperatures to use molten salts as electrolytes to combine a high current density and energy density.

The first molten salt batteries to be produced were single-use thermal batteries developed by Georg Otto Erb to be used in the V-2 rocket during World War 2 (Guidotti & Masset, 2006). It was not until Ford Motor Company invented the Na-S liquid metal battery in 1966 that the first MSB designed for EV energy storage was produced, however, R&D into its application for stationary energy storage did not begin until 1983 (Wen *et al.*, 2008).

The first patent for the sodium nickel chloride (ZEBRA) battery was applied in 1978. These MSBs are now commercialised by FZSoNick who are looking to explore their use in a range of applications including grid-level energy storage (Manzoni, 2015).

The latest MSB technology is the liquid metal battery (LMB). Although R&D into LMB's began in the 1900s with advancements in the electrolytic production of high-purity aluminium; it was not until the recent increase in renewable deployment that a resurgence of interest into LMB's for stationary storage application has occurred (Kim et al., 2013).

MSB's are increasingly gaining interest as a fitting solution to the increasing reliance on intermittent renewables in the energy mix. Since some (or all for LMBs) of the components are liquid, MSBs have the potential to combine a high energy efficiency and current density with a long cycle life, simplified manufacturing scheme, and low-cost material composition to meet the unique demands of grid-scale energy storage. (Kim *et al.*, 2013; Nitta, Inazawa & Sakai, 2013)

Furthermore, MSBs' high-rate capabilities could enable them to serve both energy and power grid-scale energy storage applications allowing for more attractive economics. This versatility could allow MSBs to perform applications that require long (several hours) discharge times such as storing energy during periods of low power demand to be distributed when power demand is high; and applications that require short discharge times such as frequency regulation and spinning reserves (Kim *et al.*, 2013).

The ZEBRA battery and LMBs are amongst the most promising MSB technologies for grid-scale applications. Despite large R&D efforts over the last few decades, there are still no existing elevated temperature systems that are cost-competitive in terms of performance and cost when compared to alternative storage solutions (Lu *et al.*, 2013) Furthermore, there are currently no storage option that meet the EU Strategic Energy Technology (SET) plan target of <0.06 $/kWh/cycle which aims to facilitate the transition towards a climate neutral EU energy system (SOLSTICE, 2021a; European Commision, 2021).

As a result of these limitations, the EU-funded SOLSTICE project was created to develop two Na-Zn molten salt battery concepts to be used for stationary energy storage. The first concept builds upon the existing ZEBRA technology, replacing their Ni electrode with cheaper Zn. The second concept is an all liquid-cell that will apply the same chemistry as the first concept yet reduce the cost further by removing the need for a ceramic electrolyte (SOLSTICE, 2021b).

2.3 ZEBRA Battery

The sodium nickel chloride (NaNiCl) ZEBRA battery consists of a nickel (Ni) and sodium chloride (NaCl) based cathode and molten sodium (Na) anode separated by a β-alumina solid ceramic electrolyte which is only conductive for Na^+ ions (Sakaebe, 2014). The overall reaction of the cell is shown in Equation 1:

$$2Na + NiCl_2 \leftrightarrow 2NaCl + Ni \qquad E = 2.58V \tag{1}$$

The NaNiCl cell operates at high temperatures between 270ºC and 350 ºC with a theoretical electric potential of 2.58V and specific energy of 140Wh/kg (Sudworth, 2001).

To avoid any issues with handling pyrophoric Na metal and anhydrous NiCl, the ZEBRA battery is assembled in the discharged state using a mixture of NaCl, Ni powder, and sodium tetra chloroaluminate ($NaAlCl_4$) which are all safe to handle (Shamim *et al.,* 2021). When the battery is charged the Na and NiCl ions are formed from the Ni powder and NaCl. The Na^+ ions then move through the ceramic electrolyte and fill the anodic compartment (Manzoni, 2015).

A basic schematic of the charged ZEBRA cell can be seen in Figure 1, where it shows the cell contains a Ni current collector for the positive electrode and a Ni-coated stainless steel cell case which also acts as the negative current collector.

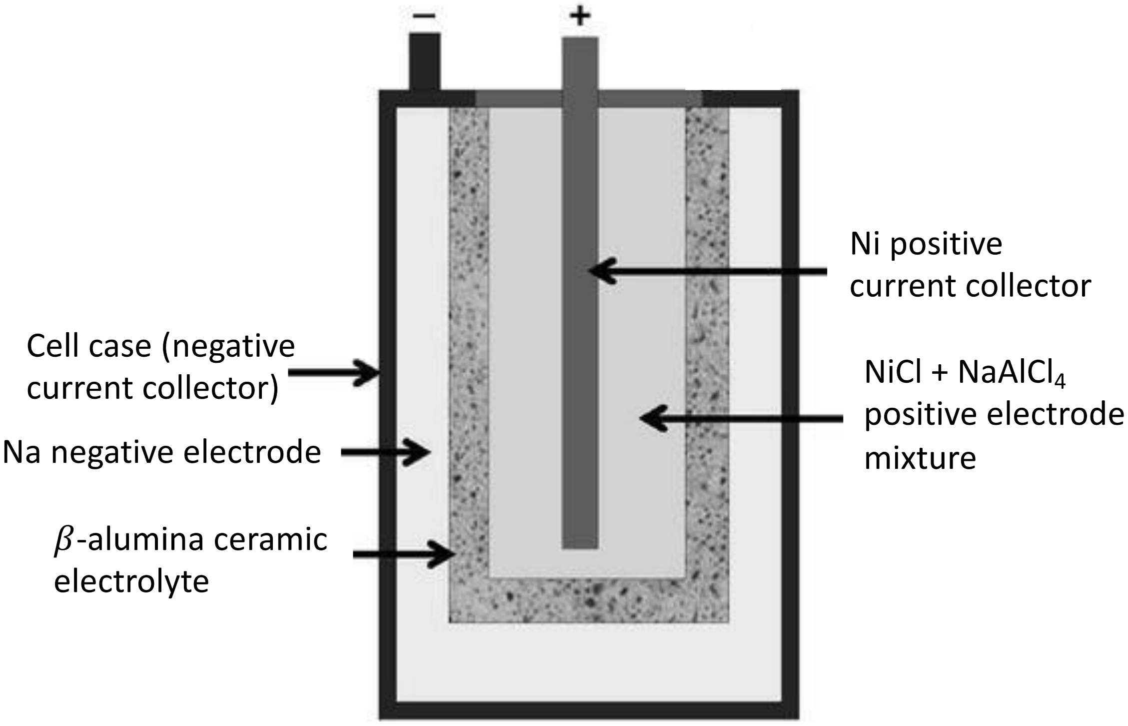


Figure 1: Schematic diagram of the charged ZEBRA cell. Modified from (Sakaebe, 2014).

The ZEBRA battery system benefits from abundant active materials, a long cycle life (>3000 cycles), low environmental impact, high safety and low maintenance that make it an attractive option for large-scale energy storage applications (Manzoni, 2015; Hartenbach, Bayer & Dustmann, 2013). Due to these advantageous features, FZSoNick, who operate a commercial ZEBRA battery production facility, are exploring the battery's utility in grid-level energy storage (Shamim *et al.*, 2021; FZSoNick, 2021).

However, despite their advantages, the relatively high cost of ZEBRA batteries has inhibited their deployment for large scale energy storage applications, with the main cost driver being the Ni metal used in the cathode (Galloway, 2003).

2.4 Solid-electrolyte Na-Zn Battery

Due to the cost limitations of the ZEBRA battery, SOLSTICE will develop a solid electrolyte Na-Zn that improves on the ZEBRA battery by replacing the costly Ni-electrode with cheap and abundant zinc (Zn). This change should minimally affect the overall ZEBRA design; thus, fast commercialisation should be achievable (SOLSTICE, 2021a).

The solid electrolyte Na-Zn cell will be akin to the ZEBRA cell with abundant active materials, a long cycle life (>4000 cycles), low environmental impact, high safety, and low maintenance. As well as a similarly high operational temperature of ≈300 ºC and same β-alumina solid ceramic electrolyte which is only conductive for Na^+ ions (SOLSTICE, 2021a).

Assuming a similar cell behaviour as ZEBRA batteries, replacing the Ni electrode with Zn will result in the overall reaction shown in Equation 2 (Xu et al., 2016).

$$ZnCl_2 + 2Na \leftrightarrow Zn + 2NaCl \qquad E = 2V \tag{2}$$

This reaction would result in a voltage of ≈2V, a theoretical specific capacity of 294 Ah/kg and theoretical specific energy of 570 Wh/kg (SOLSTICE, 2021a).

Zn was chosen as the optimal Ni-electrode replacement as this new chemistry promises similar levels of safety and performance as the ZEBRA battery at a reduced cost. This is largely due to the cost of Zn being around 10% of that of Ni, equating to a cost reduction of almost 20% when compared to the ZEBRA battery price (Lu *et al.*, 2018, 2013).

Furthermore, while Zn is less abundant than Ni, it has the 4th highest annual mining production of all metals with many of these mining operations occurring in the EU. This has the added benefit of reducing dependence on importation which is important in the transition to a carbon-neutral economy (Lee *et al.*, 2020).

2.5 All-liquid Na-Zn Battery

The second concept SOLSTICE is looking to develop is an all-liquid Na-Zn cell. The all-liquid cell will be closely related to the solid-electrolyte cell, with the main differences being its higher operating temperature of 600 ºC, and the all-liquid state of matter of the active materials (SOLSTICE, 2021a).

Due to the all-liquid nature of the cell, it will share many characteristics with LMBs and benefit from having scalability at the cell level. This scalability will allow further cost reduction to the solid electrolyte concept due to their favourable surface to volume ratio. Additionally, further cost reductions are also expected due to the all-liquid cell not requiring a ceramic electrolyte (SOLSTICE, 2021a).

Currently, this cell concept is in the very early stages of development, however, it is already being investigated as an attractive option to balance the electricity fluctuations in energy-intensive aluminium production plants. By locating the battery in an idled potline, the large all-liquid Na-Zn cells could potentially be a very effective strategy to increase the power cycling window by acting as a power buffer (Solheim et al., 2017).

2.6 Cost Estimation

The Na-Zn chemistry combined with the simple battery designs should make these concepts very cost-competitive. Due to the all-liquid cell being in the very early stages of development there are currently no accurate cost estimations for this novel battery concept, nevertheless, SOLSTICE estimate a cost of 146 $/kWh is possible by 2030 (SOLSTICE, 2021a).

This study does not make a cost estimation for the all-liquid Na-Zn battery due to the insufficient data available on this battery concept. Instead, this study highlights the necessary future developments needed to make a valid cost estimation possible.

Contrastingly, a few estimates have been made for the solid-electrolyte Na-Zn battery concept in previous literature based on the material and production costs of the related ZEBRA battery. SOLSTICE (2021a) estimates a cost of 160 $/kWh by 2030 when commercialisation is realistic, while Lu *et al.* (2018) estimate a cost reduction of 20% compared to ZEBRA is possible, equating to a cost of between 80 and 160 $/kWh based on ZEBRA price estimates (Soloveichik, 2011; Sufyan *et al.*, 2019).

However, these cost estimates are solely based on the altered electrode material composition from replacing the Ni electrode with Zn and do not consider potential changes in the battery design, assembly, electrochemistry, and other battery system components. This emphasises the need for a cost model to make a reasonable estimate on the potential price of the solid-electrolyte Na-Zn battery based on the most up-to-date primary and secondary data available.

As there is currently insufficient literature on cost projections on the novel Na-Zn battery, this study has evaluated the cost estimate methods of other battery technologies.

The main cost model studied is the Battery Performance and Cost (BatPaC) model, this model is a calculation-based bottom-up cost engineering model built using Microsoft® Excel Spreadsheets. The model accounts for every cost factor by incorporating input parameters on the batteries design, materials, electrochemical characteristics, and manufacturing process to estimate the operational and manufacturing cost of Lithium-ion batteries. Since this is a bottom-up method, this model allows the user to assess the cost effects of the individual input parameters and evaluate the main cost drivers of the battery system

This study takes inspiration from the BatPaC model by developing a bottom-up engineering cost model using Microsoft® Excel spreadsheets for the Na-Zn battery system. The model incorporates input parameters on the battery's design, materials, electrochemical characteristics, and assembly to estimate the overall cost of the Na-Zn battery system. Consequently, the main cost drivers and potential cost reductions can be assessed and evaluated.

3.0 Methodology

3.1 Cost Projection Methods

There are a variety of cost projection techniques that have been developed that can be used to estimate the costs of batteries. These include learning curve analysis, expert elicitation, and bottom-up cost modelling.

Learning curve analysis is an approach that explores the relationship between market growth and cost reduction to predict future costs (Gross *et al.*, 2013). However, learning curve analysis is heavily reliant on historical cost data and trends and thus this method is not appropriate to project the cost of the novel Na-Zn battery where historical data is not available. (Jaber, 2019).

The second approach of expert elicitation is the procedure of acquiring probabilistic belief statements from experts about quantities or parameters (Colson & Cooke, 2018). This method could use structured interviews with Na-Zn battery experts or potential manufacturers within the SOLSTICE consortium to enquire and gain information on the cost drivers of the battery technology. Due to the novel nature of the Na-Zn battery, expert elicitations are advantageous in providing expert quantitative beliefs on important battery cost drivers and components that are not available in published literature (Usher & Strachan, 2013). Nevertheless, the reliability of this approach is dependent on the individual experts' subjective beliefs and their methods of quantifying uncertainties, thus expert elicitations cannot be the only cost projection method used in this study as elicited probabilities need to be supplemented with other types of evidence (Colson & Cooke, 2018).

Finally, the bottom-up modelling approach disaggregates the battery technology into sub-systems to analyse the individual cost contributions of the components as input parameters into the model to project the overall system cost. The required information on the individual components and cost contributors can be acquired from relevant published literature or through expert elicitation with Na-Zn molten salt battery experts (Gross *et al.*, 2013). Bottom-up analysis has advantages for use with a novel battery technology: such as being able to highlight the major battery system cost drivers, which can be used to identify any changes that can be applied to reduce system cost in the early stages of development (Mukora *et al.*, 2009).

Furthermore, contrastingly to learning curve analysis bottom-up modelling does not rely on historical trends and is thus suitable for this novel battery technology (Gross *et al.*, 2013).

Based on the suitability of these methods, this study combines relevant secondary data from desk research with primary data collected through expert elicitations with expert members of the SOLSTICE consortium to use as input parameters in a bottom-up engineering cost model that estimates the investment and operational cost of the novel Na-Zn solid electrolyte molten salt battery.

3.2 Desk Research

In this study, previous literature was reviewed through desk research to collect relevant secondary data on the solid electrolyte Na-Zn molten salt battery to be used as input parameters in the created bottom-up engineering cost model. The relevant secondary data collected include the battery design, the components that make up the battery system, the component materials and material costs, and the electrochemical characteristics of the Na-Zn battery.

Due to limited publications on this novel battery technology, most of the secondary data collected on the battery system components and materials were from published literature on ZEBRA batteries. This is appropriate as the solid electrolyte Na-Zn battery concept aims to build on the existing ZEBRA technology, and other than changing the electrode material from Ni to Zn SOLSTICE plans to minimally affect other system components to allow for fast commercialisation (SOLSTICE, 2021a).

3.3 Expert Elicitation

For this study, expert interviews were carried out with six SOLSTICE consortium members to aid in collecting the most up to data and expert information on the Na-Zn molten salt battery. The consortium members interviewed were SINTEF, Polito, Quantis, EMPA, HZDR and FZSoNick.

Before expert interviews could be carried out the submission and approval of the ICREC - SETREC ethics application form (See Appendix A) was required by the CEP Research Ethics

Panel to ensure any research carried out was ethically sound. Once the ethics application form was approved, the six consortium members were contacted via email to schedule an online semi-structured interview to take place on Microsoft Teams®.

A presentation was created and emailed to interviewees in advance of the interview. The presentation included a scope of the project to give interviewees a background on the research being conducted and an indication of what data would be valuable to the project, flow charts on the battery components and materials to allow expert feedback on the secondary data collected, and the interview question list to give interviewees time to prepare responses ahead of the interview.

Relevant primary data collected from the interviews were utilised as input parameters in the bottom-up model unavailable in published literature or used to refine the secondary data that had been collected on battery's characteristics, components, and materials to improve the accuracy of the cost model.

3.4 Bottom-up Modelling

For this study a bottom-up modelling cost projection approach was most appropriate as this method does not rely on historical trends which are not available for the novel Na-Zn battery (Gross *et al.*, 2013).

In this study the bottom-up model was created in Microsoft® Excel and consisted of three spreadsheets working in conjunction. The first spreadsheet, the input sheet, was where the primary and secondary data collected during desk research and expert elicitations were logged. This consisted of input parameters on relevant battery design details such as volumes and thicknesses, battery component material costs and dimensions, and various electrochemical characteristics of the Na-Zn battery such as the theoretical electric potential and current.

The second spreadsheet was the calculation sheet where the input parameters were synthesised to calculate any useful outputs. These include the mass and volume of active materials, electric potential and energy, battery components mass and material cost, assembly cost and energy costs. These calculations were then combined to calculate the total battery system costs.

Finally, the output sheet highlighted the most important outputs from the calculation sheet. This included the cost per cell, cost per battery (assuming an 18.4 kWh battery consisting of 240 cells) and cost per kWh of all the individual cell components, BoS (Balance of System) components, assembly, energy, and the total battery system. The total battery system cycle cost was also shown.

3.5 Electrochemistry of Na-Zn Molten Salt Batteries

3.5.1 Overall Electric Potential

The overall potential of the cell (ε_{cell}) is determined by the theoretical potential (ε_{rev}) minus the incurrent losses caused by ohmic losses (ε_{ohm}) , concentration overpotential (ε_{conc}) , and charge transfer resistance (ε_{tran}) as seen in Equation 3 (Wang *et al.*, 2015).

$$\varepsilon_{cell} = \varepsilon_{rev} - \varepsilon_{ohm} - \varepsilon_{conc} - \varepsilon_{tran} \tag{3}$$

3.5.2 Theoretical Electric Potential

The theoretical electric potential of the Na-Zn cell is determined by the oxidation and reduction reactions shown in Equations 4&5 that form the overall cell reaction shown in Equation 6 (SOLSTICE, 2021a; Xu et al., 2016).

Anode:

$$2Na \leftrightarrow 2Na^{+} + 2e^{-} \tag{4}$$

Cathode:

$$Zn^{2+} + 2e^{-} \leftrightarrow Zn \tag{5}$$

Overall reaction:

$$ZnCl_2 + 2Na \leftrightarrow Zn + 2NaCl \qquad E = 2V \tag{6}$$

The theoretical electric potential of the Na-Zn overall reaction is 2V.

3.5.3 Ohmic Loss

Ohmic losses (ε_{ohm}) take place due to the resistance to the flow of protons in the electrolyte and electrons in the electrodes (Zhao & Xu, 2009). The voltage drop can be estimated by multiplying the cell current (*I*) by the internal cell resistance (R) as shown in Equation 7. The internal resistance can be evaluated by the resistances of the electrolyte, current collector (CC), and the resistance from contact.

Equation 8 includes the equations for the electrolyte and current collector resistances where A is the active area, t is the thickness and ρ is the resistivity.

$$\varepsilon_{ohm} = I * R(\text{electrolyte} + \text{CC} + \text{contact}) \tag{7}$$

$$\varepsilon_{ohm} = I * \frac{\rho_{electrolyte} * t_{electrolyte}}{A_{electrolyte}} + \frac{\rho_{CC} * t_{CC}}{A_{CC}} + \mathrm{R}_{contact}) \tag{8}$$

3.5.4 Concentration Overpotential

Concentration overpotential (ε_{conc}) (Equation 9) occurs due to the incurred concentration gradient of the reactants in the electrolyte and on the electrode surface from the slowness in mass transport during the cell reaction (Barbir, 2013; Menictas, Skyllas-Kazacos & Lim, 2014).

$$\varepsilon_{conc} = c * \ln\left(\frac{C_B}{C_S}\right) \tag{9}$$

Where c is a constant, C_B is the bulk concentration of reactant in the electrolyte, and C_S is the concentration of reactant at the electrode surface

3.5.5 Charge Transfer Resistance

Charge transfer resistance (ε_{tran}) (Equation 10) occurs because of energy losses due to the slowness of electrochemical reactions at the anode and cathode (Menictas, Skyllas-Kazacos & Lim, 2014).

$$\varepsilon_{tran} = \alpha * \ln\left(\frac{i}{i_o}\right) \tag{10}$$

Where α is a constant, i is the current density and i_o is the reaction exchange current density.

c in Equation 9 and α in Equation 10 are difficult to determine for the novel Na-Zn battery so for this study the concentration overpotential and charge transfer resistance are assumed to be 9% and 1% of the total electric potential losses respectively. These percentages are based on primary data collected during expert interviews.

3.5.6 Energy per Cell

The energy per cell (E_{cell}) was calculated by multiplying the overall electric potential of the cell (ε_{cell}) as calculated above by the capacity per cell (C_{cell}) obtained from secondary data, as shown in Equation 11.

$$E_{cell} = \varepsilon_{cell} * C_{cell} \tag{11}$$

3.6 Battery System Material Cost

The Na-Zn battery system is divided into cell components and balance-of-system (BoS) components as shown in Figure 2. The total material cost of the overall battery system is the sum of the material costs of the individual components within these sub-systems.

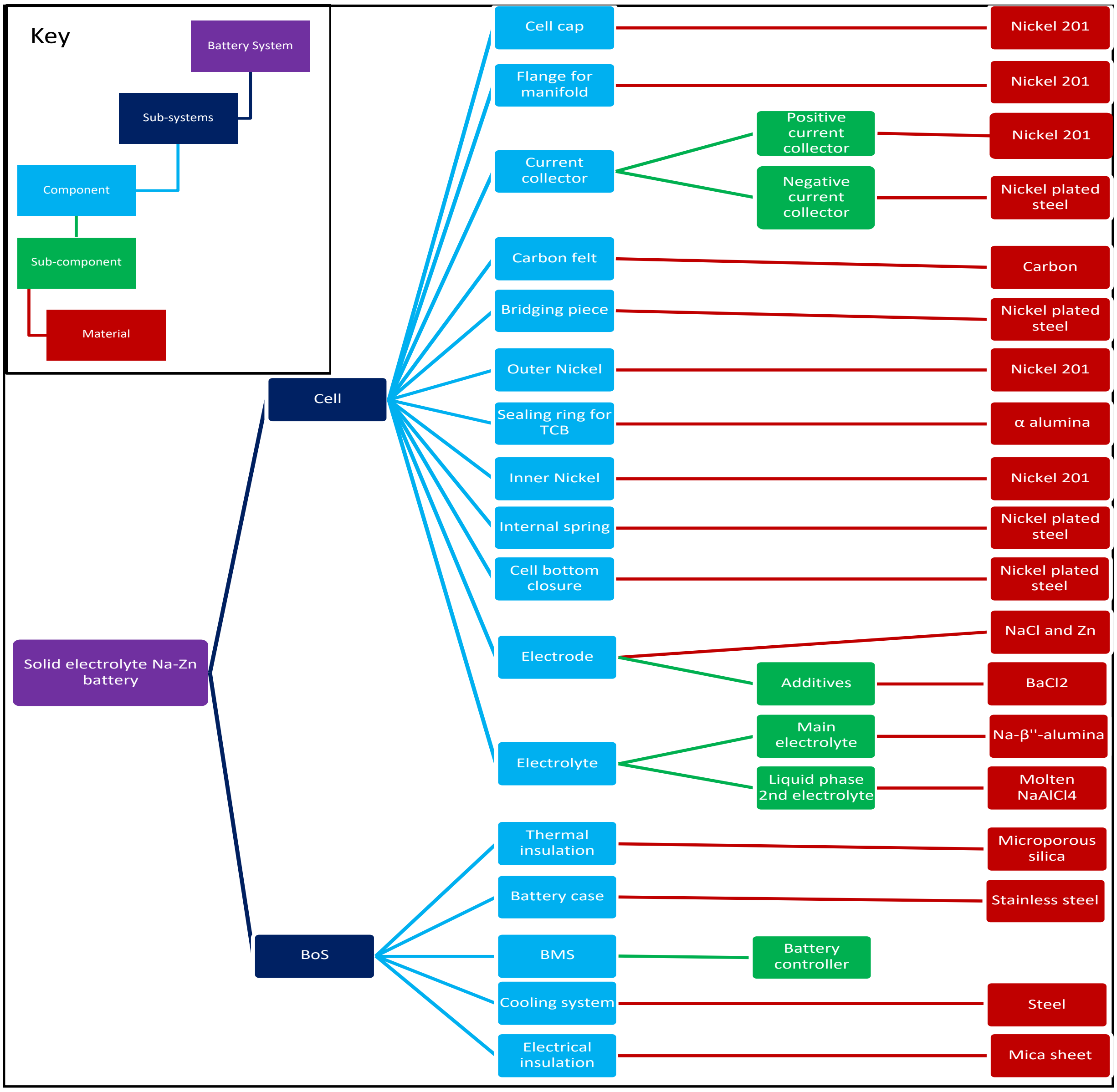


Figure 2: Flow chart on the Na-Zn solid electrolyte battery system components and materials.

3.6.1 Cell component cost

The cost of cell components was determined by multiplying the mass of the components per cell by the cost per kg of the individual components' material.

Zn and NaCl

To calculate the mass of the active materials Zn and NaCl per cell, first, the overall reaction (Equation 6) was used to calculate the mass of each active material (AM) involved in the reaction (Equation 12) and the theoretical capacity (Equation 13) of the overall reaction.

$$Mw_{AM} = Mm_{AM} * M_{AM} \tag{12}$$

$$C_{rev} = \frac{V * F * 1000}{3600 * (Mw_{Zn} + Mw_{NaCl})} \tag{13}$$

Where Mw is the molecular weight used in the overall reaction, Mm is the molecular mass of the active material, M is the Moles required for the active material in the reaction, C_{rev} is the theoretical capacity, V is the valence of reaction, and F is the Faraday constant.

The percentages of the individual active materials involved in the reaction ($Percentage_{AM}$) (Equation 14) were then combined with the theoretical capacity and capacity per cell to equate the mass of the active materials per cell as shown in Equation 15. When the mass of Zn was calculated the percentage dead mass had to be accounted for in the equation.

$$Percentage_{AM} = \frac{Mw_{AM}}{(Mw_{Zn} + Mw_{NaCl})} * 100 \tag{14}$$

$$Mass_{AMcell} = Percentage_{AM} * (\frac{C_{cell}}{C_{rev}}) \tag{15}$$

Where $Mass_{AMcell}$ is the mass of each active material required per cell and C_{cell} is the capacity per cell.

Secondary electrolyte

The mass of the molten $NaAlCl_4$ secondary electrolyte was determined by assuming it occupied 50% of cathodic volume based on primary data from the expert interviews. This required equating the volume of the active materials (Vol_{AM}) Zn and NaCl as shown in Equation 16.

$$Vol_{AM} = \frac{Mass_{AMcell}}{d_{AM}} \tag{16}$$

As $NaAlCl_4$ was assumed to occupy 50% of cathodic volume $Vol_{NaAlCl4} = Vol_{Zn} + Vol_{NaCl}$, therefore, the mass of the secondary electrolyte can be calculated as shown in Equation 17.

$$Mass_{NaAlCl4} = Vol_{NaAlCl4} * d_{NaAlCl4} \tag{17}$$

Additives

The mass of the additive $BaCl_2$ was determined by assuming its mass was 4% of the Zn and NaCl active materials combined mass based on primary data from the expert interviews.

ZEBRA cell components

The remaining component masses are assumed to be identical to the components in the ZEBRA battery. Therefore, the masses of the remaining components were determined using the ZEBRA cell design to calculate the volumes of the components and then multiplying this by the density of the component material. The cell design and component material data were obtained through data from FZSoNick.

Cost calculation

The cost per cell of the above cell components were determined by multiplying the mass of the components per cell by the cost per kg of the individual components' material. And the cost per kWh was then calculated by dividing the cost per cell by the energy per cell.

3.6.2 Balance of System Cost

The BoS components cost was determined by multiplying the mass of the components required per battery and the cost per kg of the material that makes up the components. This information was collected from secondary data (Galloway, 2003).

The cost per cell was then calculated by dividing the cost per battery obtained by the number of cells per battery. Similarly, the cost per kWh was calculated by dividing the cost per battery by the energy per battery.

3.7 Assembly and Energy Cost

Ideally, the cell and battery assembly cost would be evaluated from the costs associated with each of the Na-Zn battery assembly steps as shown in Figure 3.

However, this is beyond the scope of this study and therefore in this study the cell assembly and battery assembly costs have been estimated as a percentage of the total cell material and BoS material costs respectfully as determined from secondary data (Lu *et al*., 2013a; Galloway, 2003).

Similarly, the total energy cost of the battery system would preferably be evaluated from the energy cost associated with each battery assembly step and operation, however, this was also beyond the scope of this study and was determined from secondary data (Galloway, 2003).

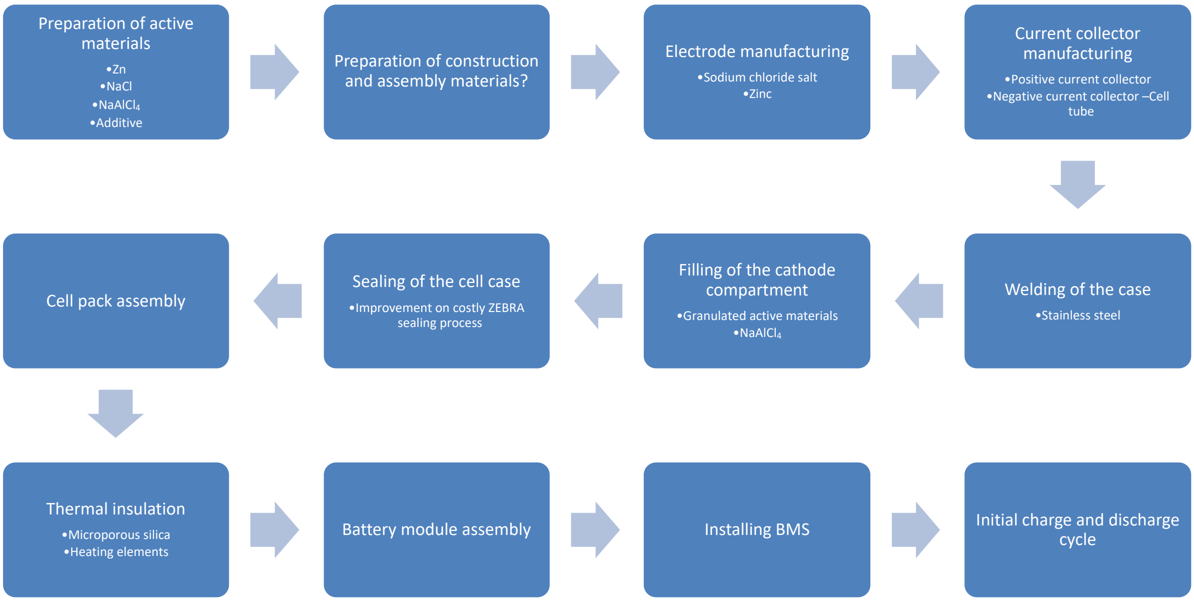


Figure 3: Flow chart on the Na-Zn solid electrolyte assembly steps.

3.8 Total Cost

The total cost of the Na-Zn battery system cost per cell was calculated as the sum of the total cell component and balance of system material costs per cell, the assembly cost per cell and the energy cost per cell.

The cost per kWh was then equated by dividing the cost per cell by the energy per cell.

Finally, the cycle cost was determined by dividing the cost per kWh by the Na-Zn battery cycle capacity.

3.9 Monte Carlo Method

The Monte Carlo method was used to automatise parameter space and assess the uncertainty on the total costs based on the ranges of values attributed to certain input parameters.

The mean and ranges of the input parameters varied were determined based on the following hierarchy:

- Firstly, previous literature was reviewed to assess any parameter uncertainties or any discrepancies in the parameters value between different papers. This was then used to determine an appropriate mean and range of values for the given parameter.

- If there was insufficient data from literature the mean and range were determined from primary data via the expert interviews.

- Finally, in cases where there was insufficient primary and secondary data, the input parameters were assumed to have an uncertainty of ±10% based on Monte Carlo analysis completed in published literature (Lewis & Bridle, 2002).

The Monte Carlo method was used on the bottom-up cost model to assess the uncertainty in the total cost estimates by automating the input parameter space within their attributed range of uncertainty based on the review of published literature and expert elicitations. Once the mean and range of the uncertainty for each input parameter had been determined, the Monte Carlo method was carried out by generating 1000 values for each input parameter assuming a normal distribution centred around the mean with a standard deviation of 0.1 and a cut off at the upper and lower range limits. These values were then input into an excel spreadsheet and used to generate 1000 total costs that presented the uncertainty in the total cost estimates.

4.0 Results

Cost results displayed below will be shown to 2 decimal places (dp), except for cycle costs which will be displayed to 2 significant figures (sf). All percentage uncertainties will be displayed to 3 sf.

4.1 Total Costs

The bottom-up model generated the total cost per cell (\$/cell), per battery (\$/battery), and per kWh (\$/kWh) as well as the total cycle cost (\$/kWh/cycle) as shown in Table 3.

Table 3: Table summarising the total cost per cell (\$/cell), battery (\$/battery), kWh (\$/kWh) and the total cycle cost (\$/kWh/cycle).

	\$/Cell	**\$/Battery**	**\$/Kwh**	**\$/Kwh/Cycle**
Na-Zn Total Cost	8.77	2105.27	114.15	0.025

As shown in Table 3 the bottom-up model resulted in a total Na-Zn battery system cost per cell of \$8.77, cost per battery of \$2105.27, cost per kWh of \$114.15 and cycle cost of \$0.025.

These total costs are a summation of the cell component costs, BoS component costs, assembly costs and energy cost. A table summarising all the individual cost components of the Na-Zn battery system can be found in Appendix B.

For these results, the mean of all the input parameters were used. For the cost per cell calculation, the cells had a capacity of 39Ah and an energy capacity of 0.077 kWh. For the cost per battery, the battery system consisted of 240 cells generating a total energy capacity of 18 kWh, finally, for the cycle cost, the cycle capacity was assumed to be 4500 cycles.

4.2 Cost Breakdown

A pie chart displaying the percentage cost breakdown of the total Na-Zn solid electrolyte system cost can be seen in Figure 4.

Figure 4 shows that the main cost contributors are the cost of the cell components, the battery assembly cost, and the cell assembly cost occupying 41.4%, 19.9% and 17.6% of the total battery system cost per kWh respectively.

It can also be seen that the main contributors to the cell component cost are the cell tube the secondary electrolyte, the positive current collector and Zn contributing 12.1%, 9.8%, 6.2% and 5.2% to the total battery system cost per kWh respectively.

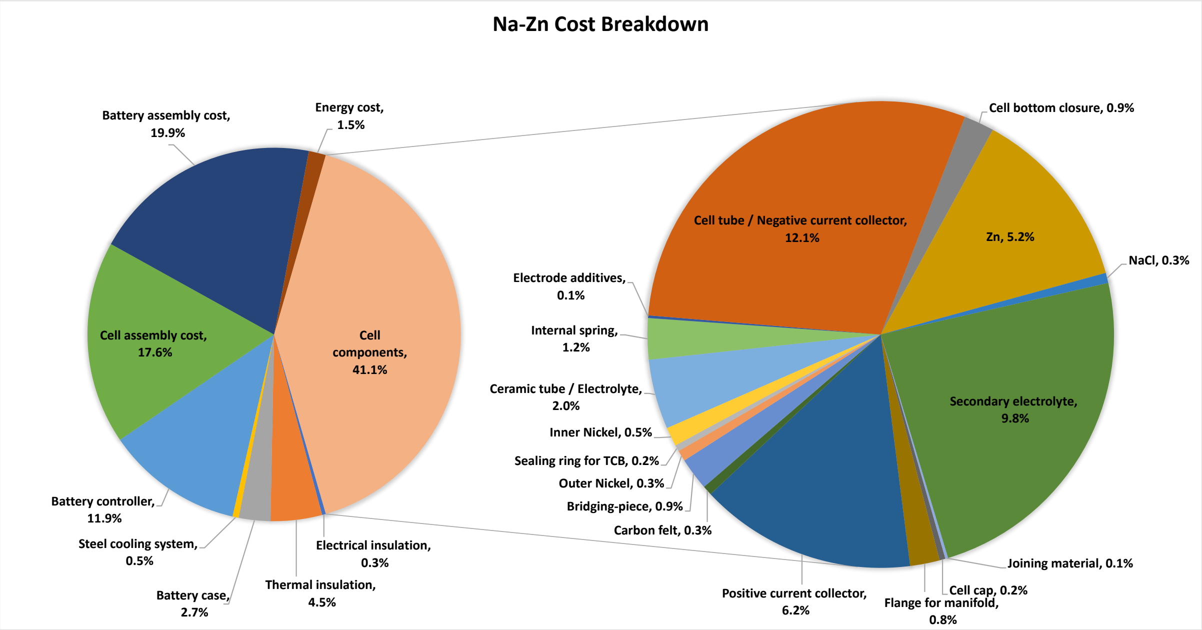


Figure 4: Pie chart showing the percentage cost breakdown of the Na-Zn solid electrolyte battery system.

4.3 Monte Carlo Results

4.31 Total cost

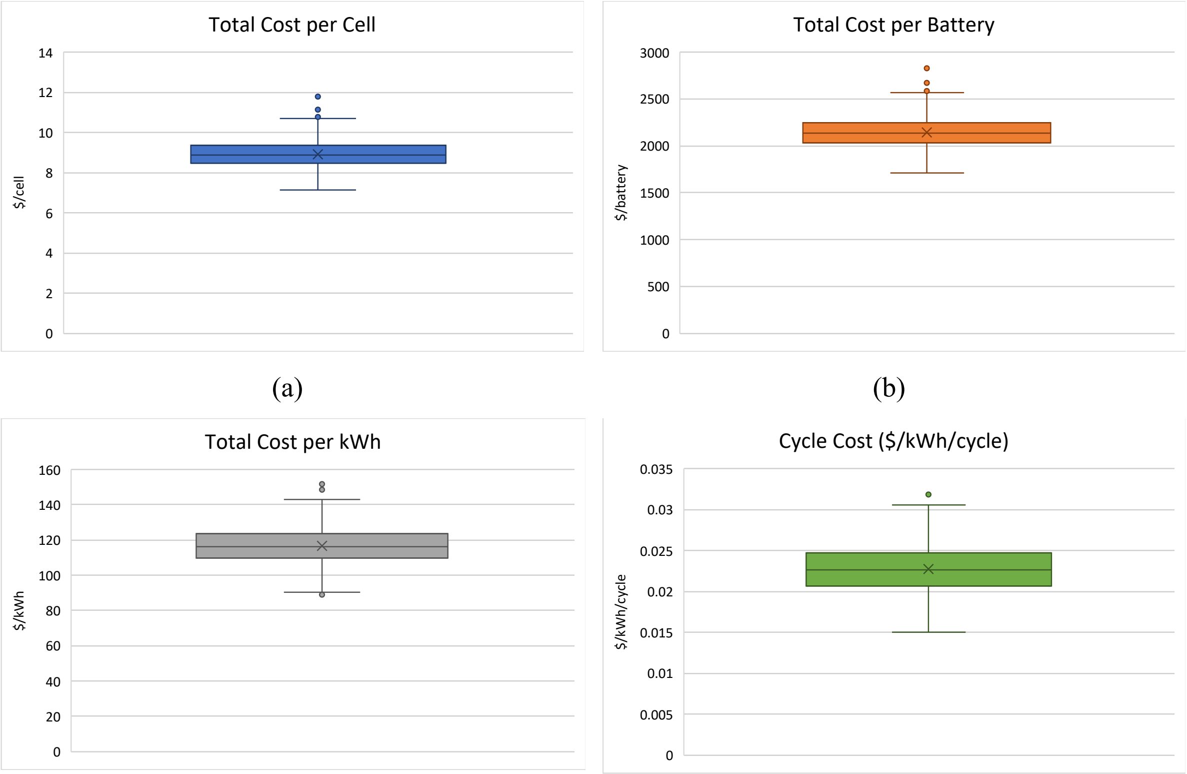
After the Monte Carlo method was applied a range of total cost values were generated displaying the uncertainty in the total cost values based on the uncertainties attributed to certain input parameters. The range of results produced by the Monte Carlo analysis for the cost per cell ($/cell), battery ($/battery), and kWh ($/kWh) as well as the total cycle cost ($/kWh/cycle) can be seen in Figure 5.

As can be seen in Figure 5a, the uncertainty in the input parameters causes a range in the total cost per cell from a low of $7.13 to a high of $10.75 with a mean of $8.92, a median of $8.89, and an interquartile range of $0.91. This equates to a mean total cost value per cell of $8.92 with a percentage uncertainty of ±20.3%.

As can be seen in Figure 5b the cost per battery values ranged from a low of $1711.08 to a high of $2581.04 with a mean of $2140.10, a median of $2132.77, and an interquartile range of $217.72. This gave a total cost value per battery of $2140.10 with a percentage uncertainty of ±20.3%.

As seen in Figure 5c the total cost per kWh ranged from a low of $90.45 to a high of $143.15 with a mean of $116.60, a median of $116.09, and an interquartile range of $13.65. This gave a mean cost value with percentage uncertainty of $116.60 ±22.6%.

Finally, in Figure 5d it is shown that the cycle cost ranges from a low of $0.015 to a high of $0.031 with a mean and median of $0.023, and interquartile range of 0.004. This equates to a mean cost value with percentage uncertainty of $0.023 ±34.8%.



(a) (b)

(c) (d)

Figure 5: Box and whiskers plots displaying the uncertainty in the total cost values generated using the Monte Carlo method on the bottom-up cost model. (a) displays the range of results for total cost per cell. (b) displays the range of results for total cost per battery. (c) displays the range of results for total cost per kWh. (d) displays the range of results for the total cycle cost. Outlier values have been highlighted as dots outside of the error bars.

4.32 Cost Breakdown

As seen in Figure 6 the total cost per kWh ($116.60 ±22.6%) is composed of the cell, BoS, assembly and energy cost per kWh. After the Monte Carlo method was applied the uncertainties attributed to certain input parameters lead to a range in these cost component values and the total cost per kWh which are displayed as box and whiskers plots in Figure 6.

As seen in Figure 6 the largest cost contributor was the cell cost. This value ranged from a low of $37.22 to a high of $60.09 with a mean of $48.12, a median of $47.95, and interquartile range of $5.69. Resulting a mean cost value with percentage uncertainty of $48.12 ±23.8%.

The second largest cost contributor was the assembly cost. As seen in Figure 6 this value has a relatively large range with a low of $26.43 to a high of $62.34 with a mean of $44.06, a median of $43.60, and interquartile range of $9.16. Equalling a mean cost value with percentage uncertainty of $44.06 ±40.8%.

The next largest contributor to the total cost per kWh was the BoS cost. As seen in Figure 6 this value ranged from a low of $18.48 to a high of $27.35 with a mean of $22.72, a median of $22.70, and interquartile range of $2.30. Equating to a mean cost value with percentage uncertainty of $22.72 ±19.5%.

Finally, not included in Figure 6 is the energy cost which had the smallest impact on the overall cost of the battery system per kWh. This value ranged from a low of $1.53 to a high of $1.87 with a mean and median of $1.70, and interquartile range of $0.12. Resulting in a mean cost value with percentage uncertainty of $1.70 ±10%.

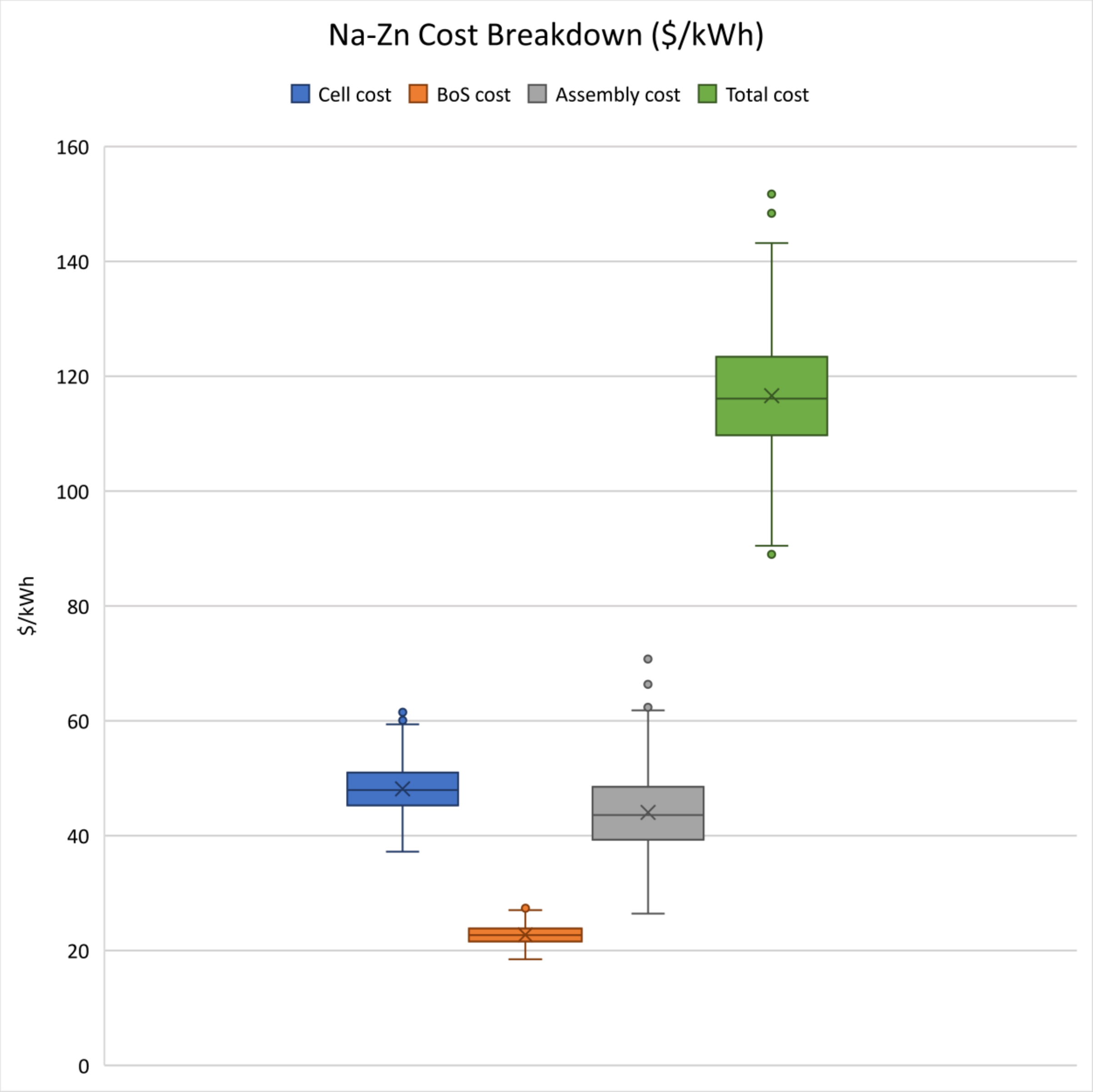


Figure 6: Cost breakdown of the Na-Zn solid electrolyte battery system. The range of values generated by the Monte Carlo method for the cell, BoS, and assembly cost components are displayed as box and whiskers plots. Any uncertainties are displayed as circles outside of the error bars.

4.4 Sensitivity Analysis

To assess how uncertainties in various model parameters affected the total cost per kWh a sensitivity analysis was performed.

A sensitivity analysis was achieved by varying the parameter being assessed between its maximum and minimum ranges while keeping all other model parameters constant at their mean. This was then cycled through all other model parameters being assessed with the spread in total cost caused by each parameter being recorded. The sensitivity in the total cost to uncertainties in model parameters can be seen in Figure 7. The sensitivity analysis results are referenced to the base total cost output of $114.15 before the Monte Carlo method was applied.

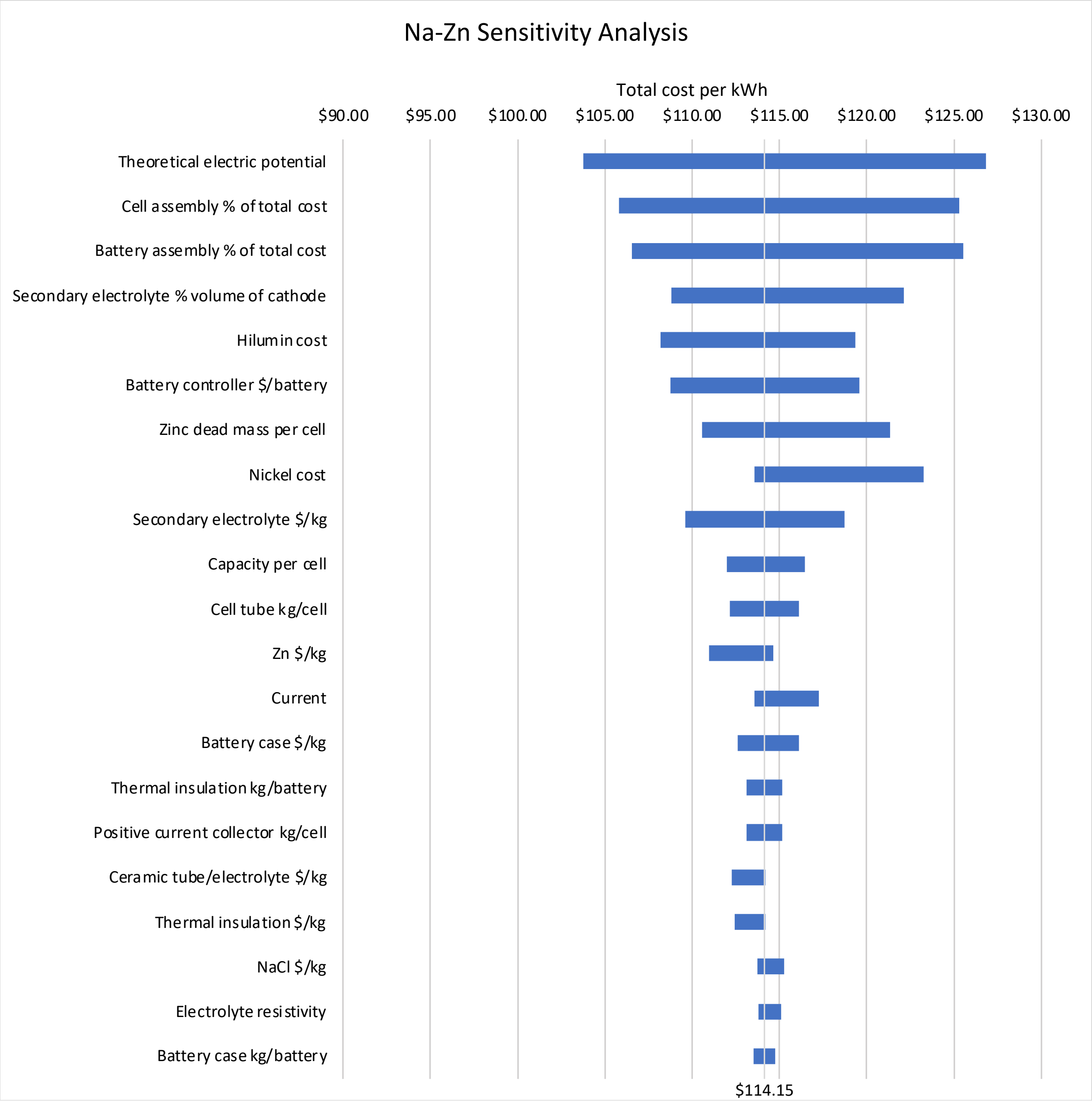


Figure 7: Tornado diagram depicting the sensitivity in the total cost per kWh to uncertainties in certain model parameters. Only parameters that caused a spread in the total cost >$1/kWh are displayed.

As seen in Figure 7, the parameters that cause the greatest sensitivity in the total cost per kWh are uncertainties in the theoretical electric potential (causing a sensitivity in the total cost per kWh ranging from $103.79 to $126.86 with a total spread of $23.07), the cell assembly percentage of the total cost (causing the total cost to range between $105.78 and $125.31 with a total spread of $19.53), the battery assembly percentage of the total cost (causing the total cost to range between \$106.57 and \$125.52 with a total spread of \$18.95), and the secondary electrolyte percentage of cathodic volume (causing the total cost to range between \$108.82 and \$122.15 with a total spread of \$13.33).

5.0 Discussion

5.1 Total Cost and Cost Competitiveness

Following Monte Carlo analysis, this study found the total cost per kWh of the Na-Zn solid electrolyte battery system to be $116.60 ±22.6%. This is in line with the estimated cost by Lu *et al.* (2018) where they proposed a cost between 80 and 160 $/kWh was possible, giving confidence to the study's estimate. This does not, however, agree with the SOLSTICE (2021a) estimate of $160 per kWh which falls outside the range of this study's total cost error bars (Figure 6). This discrepancy is likely due to SOLSTICE not considering all of the potential changes in the battery design, electrochemistry and other component material that could result in a further cost reduction when compared to the ZEBRA battery.

An initial objective of this project was to evaluate the cost competitiveness of the Na-Zn battery system against alternative energy storage solutions. As the novel Na-Zn battery is not scheduled to be commercialised until 2030, to achieve a fair cost comparison it is necessary to compare this study's bottom-up model total cost estimate with future cost projections of alternative electrical energy storage technologies. This ensures a cost comparison is possible when the Na-Zn battery is forecast to be in production and competing for deployment. The cost projections of competing energy storage technologies are shown in Figure 8 (Schmidt *et al.*, 2017).

From Figure 8 it is possible to see that the competing large-scale energy storage technologies of pumped hydro, lithium-ion, redox-flow, and electrolysis have costs per kWh of ≈$300, ≈$500, ≈$400, and ≈$150 respectively at the large-scale utility level in 2030. Therefore, the bottom-up calculated result of $116.60 ±22.6% per kWh for the Na-Zn solid electrolyte would outcompete these alternative storage options in terms of cost at the time of its commercialisation.

Furthermore, the estimated Na-Zn cycle cost of $0.023 ±34.8% is below the SET plan target of less than 0.06 $/kWh/cycle for stationary storage, meaning the solid electrolyte Na-Zn battery would be a suitable technology to facilitate the transition to a climate-neutral EU energy system.

However, Figure 8 also shows that the electrolysis price is forecast to drop to ≈$100 per kWh by 2040, thus outcompeting the Na-Zn battery in terms of cost. This would result in additional cost reductions to the Na-Zn battery system being necessary to stay cost-competitive in 2040 and onwards.

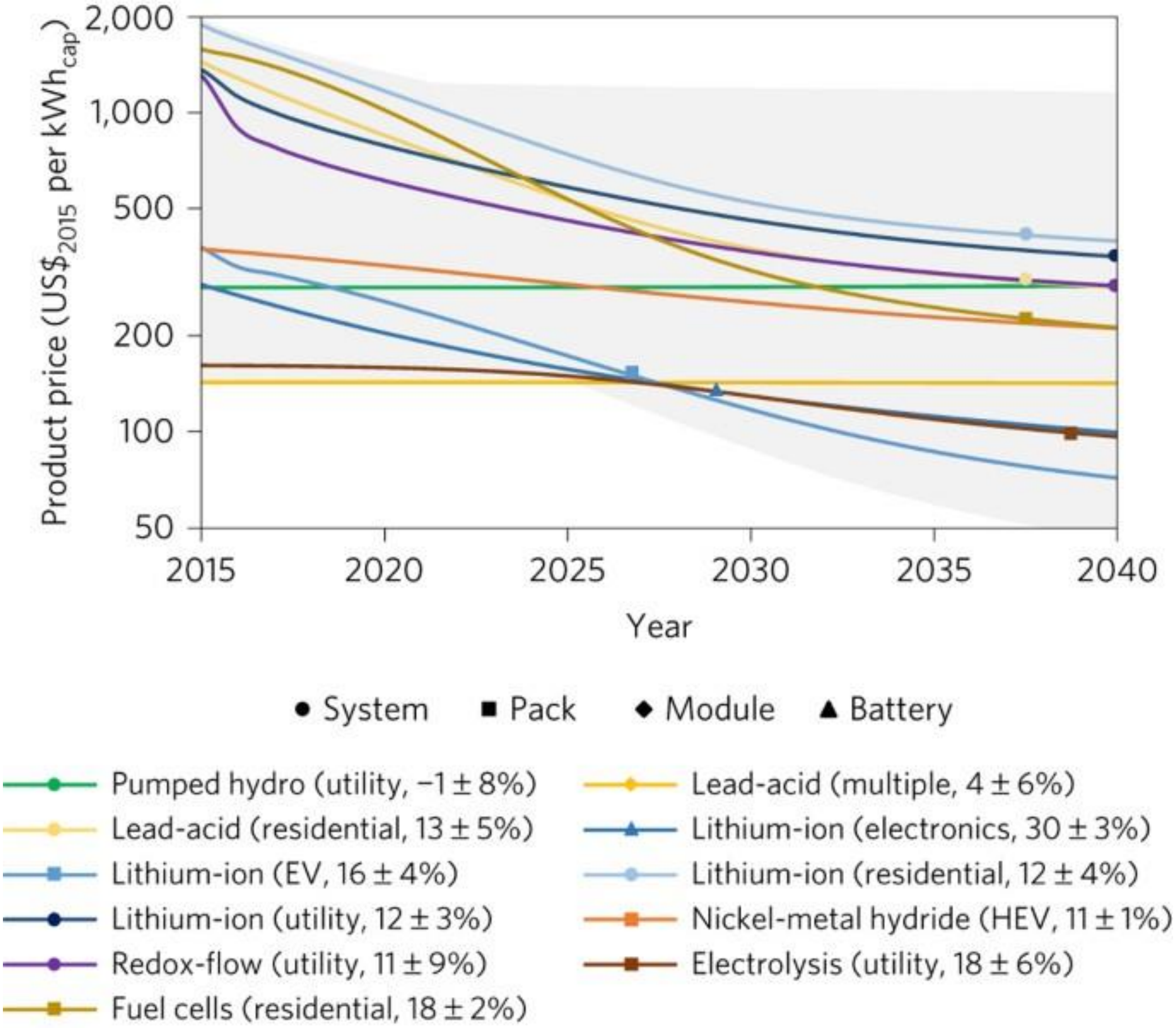


Figure 8: Cost projections of alternative energy storage solutions relative to time (Schmidt et al., 2017).

5.2 Cost Breakdown and Sensitivity Analysis

The main areas for potential cost reductions in the overall Na-Zn battery system cost are highlighted in the cost breakdown and sensitivity analysis as shown in Figures 4 and 7, respectively.

One possible solution that applies to all areas of potential cost reductions summarised below is economies of scale. This would result in lower capital costs from reduced material costs when bought at a large scale, and lower assembly costs through a larger and more automated production process.

As can be seen in Figure 4 the main cost contributors are the cost of the cell components, the assembly costs, occupying 41.4%, 37.5% of the total battery system cost per kWh respectively.

Within the cell components, the biggest cost contributor was the cell tube with a percentage cost contribution of 12.1%. This large cost is due to the cell tubes expensive Hilumin nickel-plated steel material cost of ≈$13.2/kg and large volume per cell. As can be seen in Figure 7 the cost of Hilumin has a much larger effect on the overall battery system price per kWh than the cell tube volume per cell with a spread of $11.19 compared to $3.96 respectively. Therefore, the greatest cost reduction for the cell tube could be achieved by replacing the costly Hilumin with a relatively cheaper material, such as using Zn plated steel.

The next largest cell component cost contributor is the molten $NaAlCl_4$ secondary electrolyte with a cost contribution to the overall battery system price per kWh of 9.8%. This large cost contribution is a result of the relatively high cost of ≈$7/kg for $NaAlCl_4$ and large volume per cell, occupying 50% of the cathodic volume. As seen in Figure 7, the main cost reduction potential comes from reducing the percentage volume of $NaAlCl_4$ in the cathode. The sensitivity analysis shows that by reducing the cathodic volume occupancy from 50% to 40% while keeping all other parameters constant causes the battery system cost per kWh to drop from $114.15 to $108.82.

The next largest cell component cost is the Ni positive current collector with a percentage contribution of 6.2%. This cost is mainly driven by the relatively high cost of Ni ($11.60/kg), which is supported in the sensitivity analysis where it shows that the range in Ni cost causes an overall sensitivity of $9.70 in the overall battery system cost per kWh, while the positive current collector volume per cell only causes a spread of $2.01. Therefore, this cost could be significantly reduced by using an alternative cheaper material to Ni. The Na-Zn battery concept already replaces the ZEBRA Ni electrode with Zn, so replacing the Ni current collector could also be seen as a viable option.

Finally, the fourth largest cell component cost contributor is Zn with a percentage contribution of 5.2% to the overall battery system cost. This is largely due to the dead mass required for wetting adding an additional 70% to the Zn needed in the cell reaction. As can be seen in the sensitivity analysis in Figure 7, reducing the dead mass to 60% while keeping all other parameters constant causes the battery system cost per kWh to drop from \$114.15 to \$110.54. Therefore, the greatest cost reduction could be from reducing the dead mass required per cell.

As seen in Figure 4, the next largest battery system cost contributors are the battery and cell assembly cost contributing 19.9% and 17.6% to the total battery system cost per kWh respectively. This is further supported in Figure 7 where the cell assembly percentage of the total cost (causing the total cost to range between \$105.78 and \$125.31 with a total spread of \$19.53), and the battery assembly percentage of the total cost (causing the total cost to range between \$106.57 and \$125.52 with a total spread of \$18.95) cause the second and third greatest sensitivity in the total cost per kWh respectively. A cost reduction in the assembly process could be achieved through advancements in the assembly process and making the assembly more automatized through the utilization of advanced machinery capable of dealing with a large supply of material.

As seen in Figure 7, uncertainties in the theoretical electric potential caused the greatest sensitivity in the total cost per kWh. Consequently, increases in the electric potential have the greatest cost reduction potential of all model parameters. The large sensitivity is because the electric potential directly influences the energy of each cell, this is important for the overall cost of the Na-Zn battery system as the energy per cell dictates the number of cells necessary to reach the required power rating of the battery. The more cells required, the greater the mass of material needed and the higher the material cost. However, it is difficult to improve the theoretical potential as this is determined by the active material chemistry of the cell. Nonetheless cost reductions through increasing the energy per cell could be achieved by reducing the losses incurred through ohmic losses, concentration overpotential, and charge transfer resistance, and through increasing the capacity per cell.

5.3 Limitations

This study has satisfied the original aims and objectives by estimating the overall solid electrolyte Na-Zn battery system cost through a bottom-up method that synthesises input parameters on battery materials, components, electrochemical characteristics, and assembly to estimate the total Na-Zn solid electrolyte battery cost. The study then assesses the main cost drivers and areas with the greatest cost reduction potential; and evaluates the cost competitiveness of this concept compared to the projected costs of competing energy storage technologies.

However, there are many limitations to the bottom-up model that impacted the cost estimates of the Na-Zn solid electrolyte battery:

Firstly, there were limitations in the accuracy of the input parameters, including limitations in the battery design, dimensions, assembly, electrochemical characteristics, and material cost. This caused large uncertainties in the model cost results as can be seen in Figures 5 and 6. These uncertainties are largely due to the limited primary and secondary data available for the novel Na-Zn battery technology, therefore, to reduce this limitation it is necessary to collect further data as the battery develops and becomes more refined.

This model is also limited as it assumes most of the cell components have the same material composition and mass as the ZEBRA battery. While the Na-Zn solid electrolyte battery is expected to have a similar composition to ZEBRA, discrepancies in the battery components mass and material are likely with the change in electrode chemistry. To reduce this limitation data specific to the Na-Zn composition are required to improve the accuracy of the models' input parameters related to the battery components mass and material.

Further limitations occur due to the confidentiality of information. During expert elicitations it was a common occurrence that important information for the model was confidential due to companies' interests. This impacted the accuracy of the model cost estimates as assumptions had to be made where primary data could not be collected.

There were also limitations in the model's BoS cost estimates as the components masses were not calculated through a bottom-up approach and instead the obtained from secondary data.

Another limitation in the model was the assumption that assembly cost was a percentage of the total material cost. To improve the accuracy of the assembly cost, the cost associated with each assembly step (Figure 3) could be calculated and compiled to give the overall battery system assembly cost.

The energy cost estimate was also limited as it was collected from primary data on the ZEBRA battery energy cost. This limitation could be reduced by calculating the overall energy cost by multiplying the cost per unit of energy by the energy consumed during the battery's production and operation.

There were also limitations in the concentration overpotential and charge transfer resistance values, due to the difficulty in the calculations of these values they were assumed to be a percentage of the cells overall electric potential loss. Accordingly, this reduced the accuracy of the overall potential of the cell and the overall battery system cost results.

Finally, this model is limited as it assumes a normal distribution for the uncertainty in every input parameter being varied in the Monte Carlo method. To reduce this limitation, each input parameter could be examined using primary and secondary data to determine the most appropriate distribution to be used in the Monte Carlo method.

6.0 Conclusion

6.1 Key Findings

In conclusion, the bottom-up model total cost per kWh for the Na-Zn solid electrolyte battery system of \$116.60 ±22.6% is projected to be more cost-competitive than alternative energy storage options at the time of its commercialisation in 2030. Additionally, the low battery system cycle cost of \$0.023 ±34.8% is below the SET plan target of less than 0.06 \$/kWh/cycle for stationary storage, making it a viable storage option in the transition to a climate-neutral EU energy system.

These low costs coupled with the additional benefits of abundant active materials, a long cycle life (>4000 cycles), low environmental impact, high safety and low maintenance would make the Na-Zn solid electrolyte battery an excellent prospect for large-scale grid energy storage.

6.2 Future Work

This study is unlike any research presented in the literature review as it is the first model estimating the cost of the Na-Zn solid electrolyte molten salt battery system through a bottom-up approach. Therefore, this study offers a new approach that has not only been successful in estimating the total Na-Zn battery system cost but is also unique to this research area and opens new avenues for research.

This work could be improved by the collection of more refined data on the Na-Zn solid-electrolyte battery as it develops to reduce the limitations associated with assuming most of the cell components' mass and material are the same as the ZEBRA battery.

This study should also be improved by performing a bottom-up calculation of the BoS, assembly and energy cost to make the model more complete. The BoS cost would be calculated by calculating the mass of each BoS component from the material density and volume per cell rather than obtaining the mass per battery from secondary data. The assembly and energy cost estimates would be achieved by calculating the assembly and energy cost associated with each battery production step in addition to calculating the energy cost during battery operation.

An insightful addition to this model would be to estimate future costs based on economies of scale and learning curve analysis. This was impractical for this study as learning curve analysis relies on historical cost data and trends which was not available for the Na-Zn battery at the time of completion of this study. However, when sufficient historical data becomes available a learning curve analysis would be useful in determining how competitive projected Na-Zn battery costs would be against alternative energy storage options in the future.

Finally, future studies should complete a similar bottom-up engineering cost model for the all-liquid electrolyte Na-Zn battery concept. Currently, there is insufficient data to perform a cost estimate as the concept is in the very early stages of development. Therefore, future studies should perform a bottom-up engineering cost model once the concept is more refined and sufficient data on the batteries design, assembly, electrochemistry, and material composition is available.

References

Barbir, F. (2013) PEM Fuel Cells. *PEM Fuel Cells*. [Online] Available from: doi:10.1016/C2011-0-06706-6 [Accessed: 27 August 2021].

Cash, D.W. (2018) Choices on the road to the clean energy future. *Energy Research and Social Science*. [Online] 35, 224–226. Available from: doi:10.1016/j.erss.2017.10.035.

Chen, H., Cong, T.N., Yang, W., Tan, C., et al. (2009) Progress in electrical energy storage system: A critical review. *Progress in Natural Science*. [Online]. 19 (3) pp.291–312. Available from: doi:10.1016/j.pnsc.2008.07.014.

Chen, T., Jin, Y., Lv, H., Yang, A., et al. (2020) Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems. *Transactions of Tianjin University*. [Online]. 26 (3) pp.208–217. Available from: doi:10.1007/s12209-020-00236-w.

Cheng Yang, C., Chun Wang, C., Miao Li, M. & Qing Jiang (2017) A start of the renaissance for nickel metal hydride batteries: a hydrogen storage alloy series with an ultra-long cycle life. *Journal of Materials Chemistry A*. [Online] 5 (3), 1145–1152. Available from: doi:10.1039/C6TA09736G [Accessed: 25 August 2021].

Colson, A.R. & Cooke, R.M. (2018) Expert elicitation: Using the classical model to validate experts' judgments. *Review of Environmental Economics and Policy*. [Online] 12 (1), 113–132. Available from: doi:10.1093/reep/rex022 [Accessed: 22 June 2021].

Dufo-López, R., Carvalho, M., Pasaoglu, G. & Zubi, G. (2018) The lithium-ion battery: State of the art and future perspectives Article in Renewable and Sustainable Energy Reviews · The lithium-ion battery: State of the art and future perspectives. *Renewable and Sustainable Energy Reviews*. [Online] 89, 292–308. Available from: doi:10.1016/j.rser.2018.03.002 [Accessed: 20 June 2021].

European Commision (2021) *Strategic Energy Technology Plan | Energy*. [Online]. 2021. Available from: https://ec.europa.eu/energy/topics/technology-and-innovation/strategic-energy-technology-plan_en [Accessed: 29 August 2021].

Fan, X., Liu, B., Liu, J., Ding, J., et al. (2020) Battery Technologies for Grid-Level Large-Scale Electrical Energy Storage. *Transactions of Tianjin University 2020 26:2*. [Online] 26 (2), 92–103. Available from: doi:10.1007/S12209-019-00231-W [Accessed: 25 August 2021].

Few, S., Schmidt, O. & Gambhir, A. (2016) FewSchmidtGambhir_ElecEnergy-storage_GBP (1). *Grantham Institute*.

FZSoNick (2021) *THE SALT BATTERY. - Industrial Energy Storage*. [Online]. 2021. Available from: https://www.fzsonick.com/applications/industrial-energy-storage [Accessed: 29 August 2021].

Galloway, R.C. (2003) *ZEBRA Battery-Material Cost Availability and Recycling*.

Gross, R., Heptonstall, P., Greenacre, P., Candelise, C., et al. (2013) *Presenting the Future: An assessment of future costs estimation methodologies in the electricity generation sector A report by the UKERC Technology & Policy Assessment Function*. [Online]. Available from: www.ukerc.ac.uk/support/TheMeetingPlace [Accessed: 22 June 2021].

Guidotti, R.A. & Masset, P. (2006) Thermally activated ("thermal") battery technology. Part I: An overview. *Journal of Power Sources*. [Online] 161 (2), 1443–1449. Available from: doi:10.1016/j.jpowsour.2006.06.013 [Accessed: 21 June 2021].

Hartenbach, A., Bayer, M. & Dustmann, C.H. (2013) The Sodium Metal Halide (ZEBRA) Battery: An Example of Inorganic Molten Salt Electrolyte Battery. *Molten Salts Chemistry*. [Online] 439–450. Available from: doi:10.1016/B978-0-12-398538-5.00021-4 [Accessed: 23 August 2021].

IEA (2020) *Renewables 2020 – Analysis - IEA*. [Online]. 2020. IEA. Available from: https://www.iea.org/reports/renewables-2020 [Accessed: 25 August 2021].

Jaber, M.Y. (2019) *LEARNING CURVES LEARNING CURVES Edited by*.

Kim, H., Boysen, D.A., Newhouse, J.M., Spatocco, B.L., et al. (2013) Liquid metal batteries: Past, present, and future. *Chemical Reviews*. [Online]. 113 (3) pp.2075–2099. Available from: doi:10.1021/cr300205k [Accessed: 21 June 2021].

Kubiak, P., Cen, Z., López, C.M. & Belharouak, I. (2017) Calendar aging of a 250 kW/500 kWh Li-ion battery deployed for the grid storage application. *Journal of Power Sources*. [Online] 372, 16–23. Available from: doi:10.1016/J.JPOWSOUR.2017.10.063 [Accessed: 25 August 2021].

Laporte, A. (2019) *Fact Sheet | Energy Storage (2019) | White Papers | EESI*. [Online]. 22 February 2019. Available from: https://www.eesi.org/papers/view/energy-storage-2019 [Accessed: 20 June 2021].

Lee, J., Bazilian, M., Sovacool, B., Hund, K., et al. (2020) Reviewing the material and metal security of low-carbon energy transitions. *Renewable and Sustainable Energy Reviews*. [Online] 124, 109789. Available from: doi:10.1016/J.RSER.2020.109789 [Accessed: 29 August 2021].

Lewis, A. & Bridle, S. (2002) *Cosmological parameters from CMB and other data: A Monte Carlo approach*. [Online] Available from: doi:10.1103/PhysRevD.66.103511 [Accessed: 28 August 2021].

Lu, X., Chang, H.J., Bonnett, J.F., Canfield, N.L., et al. (2018) An Intermediate-Temperature High-Performance Na–ZnCl2 Battery. *ACS Omega*. [Online] 3 (11), 15702–15708. Available from: doi:10.1021/ACSOMEGA.8B02112 [Accessed: 29 August 2021].

Lu, X., Li, G., Kim, J.Y., Lemmon, J.P., et al. (2013) A novel low-cost sodium–zinc chloride battery. *Energy & Environmental Science*. [Online] 6 (6), 1837–1843. Available from: doi:10.1039/C3EE24244G [Accessed: 28 August 2021].

Manzoni, R. (2015) Sodium Nickel Chloride batteries in transportation applications. In: *Electrical Systems for Aircraft, Railway and Ship Propulsion, ESARS*. [Online]. 4 May 2015 IEEE Computer Society. p. Available from: doi:10.1109/ESARS.2015.7101491 [Accessed: 21 June 2021].

Menictas, C., Skyllas-Kazacos, M. & Lim, T.M. (2014) Advances in Batteries for Medium and Large-Scale Energy Storage: Types and Applications. *Advances in Batteries for Medium and Large-Scale Energy Storage: Types and Applications*. [Online] 1–634. Available from: doi:10.1016/C2013-0-16429-X [Accessed: 27 August 2021].

Mukora, A., Winskel, M., Jeffrey, H.F. & Mueller, M. (2009) Learning curves for emerging energy technologies. In: *Proceedings of Institution of Civil Engineers: Energy*. [Online]. 1 November 2009 Thomas Telford Ltd . pp. 151–159. Available from: doi:10.1680/ener.2009.162.4.151 [Accessed: 22 June 2021].

Nitta, K., Inazawa, S. & Sakai, S. (2013) *Development of Molten Salt Electrolyte Battery*.

Sakaebe, H. (2014) ZEBRA Batteries. *Encyclopedia of Applied Electrochemistry*. [Online] 2165–2169. Available from: doi:10.1007/978-1-4419-6996-5_437 [Accessed: 23 August 2021].

Savaresi, A. (2016) The Paris agreement: A new beginning? *Journal of Energy and Natural Resources Law*. [Online] 34 (1), 16–26. Available from: doi:10.1080/02646811.2016.1133983.

Schmidt, O., Hawkes, A., Gambhir, A. & Staffell, I. (2017) The future cost of electrical energy storage based on experience rates. *Nature Energy 2017 2:8*. [Online] 2 (8), 1–8. Available from: doi:10.1038/nenergy.2017.110 [Accessed: 1 September 2021].

Shamim, N., Thomsen, E.C., Viswanathan, V. v., Reed, D.M., et al. (2021) Evaluating zebra battery module under the peak-shaving duty cycles. *Materials*. [Online] 14 (9). Available from: doi:10.3390/ma14092280.

Solheim, A., Osen, K.S., Sommerseth, C. & Kongstein, O.E. (2017) *Liquid Metal Batteries as a Power Buffer in Aluminium Production Plants*.

Soloveichik, G.L. (2011) Battery Technologies for Large-Scale Stationary Energy Storage. *http://dx.doi.org/10.1146/annurev-chembioeng-061010-114116*. [Online] 2, 503–527. Available from: doi:10.1146/ANNUREV-CHEMBIOENG-061010-114116 [Accessed: 30 August 2021].

SOLSTICE (2021a) *SOLSTICE - Background on Na-Zn battery*.

SOLSTICE (2021b) *SOLSTICE – Sodium-Zinc molten salt batteries for low-cost stationary storage*. [Online]. 2021. Available from: https://www.solstice-battery.eu/ [Accessed: 26 August 2021].

Sudworth, J.L. (2001) *The sodium/nickel chloride (ZEBRA) battery*.

Sufyan, M., Rahim, N.A., Aman, M.M., Tan, C.K., et al. (2019) Sizing and applications of battery energy storage technologies in smart grid system: A review. *Journal of Renewable and Sustainable Energy*. [Online] 11 (1), 014105. Available from: doi:10.1063/1.5063866 [Accessed: 30 August 2021].

Tsiropoulos I, Tarvydas D & Lebedeva N (2018) *Li-ion batteries for mobility and stationary storage applications Scenarios for costs and market growth*. In: [Online]. 2018 p. Available from: doi:10.2760/87175.

Usher, W. & Strachan, N. (2013) An expert elicitation of climate, energy and economic uncertainties. *Energy Policy*. [Online] 61, 811–821. Available from: doi:10.1016/J.ENPOL.2013.06.110 [Accessed: 26 August 2021].

Wang, W., Wei, X., Choi, D., Lu, X., et al. (2015) Electrochemical cells for medium- and large-scale energy storage: fundamentals. *Advances in Batteries for Medium and Large-Scale Energy Storage: Types and Applications*. [Online] 3–28. Available from: doi:10.1016/B978-1-78242-013-2.00001-7 [Accessed: 27 August 2021].

Wen, Z., Cao, J., Gu, Z., Xu, X., et al. (2008) Research on sodium sulfur battery for energy storage. *Solid State Ionics*. [Online] 179 (27–32), 1697–1701. Available from: doi:10.1016/j.ssi.2008.01.070 [Accessed: 21 June 2021].

Xu, J., Kjos, O.S., Osen, K.S., Martinez, A.M., et al. (2016) Na-Zn liquid metal battery. *Journal of Power Sources*. [Online] 332, 274–280. Available from: doi:10.1016/j.jpowsour.2016.09.125 [Accessed: 27 May 2021].

Zhang, C., Wei, Y.L., Cao, P.F. & Lin, M.C. (2018) Energy storage system: Current studies on batteries and power condition system. *Renewable and Sustainable Energy Reviews*.

[Online]. 82 pp.3091–3106. Available from: doi:10.1016/j.rser.2017.10.030 [Accessed: 20 June 2021].

Zhang, M., Moore, M., Watson, J.S., Zawodzinski, T.A., et al. (2012) Capital Cost Sensitivity Analysis of an All-Vanadium Redox-Flow Battery. *Journal of The Electrochemical Society*. [Online] 159 (8), A1183. Available from: doi:10.1149/2.041208JES [Accessed: 25 August 2021].

Zhao, B., Ding, Y. & Wen, Z. (2019) From Jackfruit Rags to Hierarchical Porous N-Doped Carbon: A High-Performance Anode Material for Sodium-Ion Batteries. *Transactions of Tianjin University 2019 25:5*. [Online] 25 (5), 429–436. Available from: doi:10.1007/S12209-019-00209-8 [Accessed: 25 August 2021].

Zhao, T.S. & Xu, C. (2009) FUEL CELLS – DIRECT ALCOHOL FUEL CELLS | Direct Methanol Fuel Cell: Overview Performance and Operational Conditions. *Encyclopedia of Electrochemical Power Sources*. [Online] 381–389. Available from: doi:10.1016/B978-044452745-5.00244-6 [Accessed: 27 August 2021].

van Zyl, A. (1996) Review of the zebra battery system development. *ELXVIER Solid State Ionics*. 86, 883–889.

ICREC - SETREC APPLICATION FORM

Appendix A – Ethics Application Form

Part 1 (to be completed by all)

Details of Principle Investigator	
For all projects the Principal Investigator (PI) must be employed by Imperial College London or hold an honorary contract. For all student projects, the student's supervisor must be named as PI. Student, co-investigator and collaborator details must be added to Section 14.	
Name (incl. title)	Dr Iain Staffell
Position (at Imperial College London)	Senior Lecturer in Sustainable Energy
Faculty	Natural Sciences
Division/ School/ Department	Centre for Environmental Policy
Email *Imperial College email*	i.staffell@imperial.ac.uk
7. Summary of skills (experience relevant to the study and in any procedures to be used) *(350 characters max)*	Iain's experience centres around decarbonising electricity systems, ranging from the economics of battery storage and productivity of offshore wind farms to efficient ways of integrating renewables into electricity markets. Iain holds degrees in Physics, Chemical Engineering and Economics and is a Senior Lecturer in Sustainable Energy at the Centre for

Research type	Are you conducting research? Yes ☒ No ☐ Are you conducting a service evaluation, audit or public involvement? Yes ☐ No ☒ Does your study only involve analysis of secondary data which is publicly available, and permission is not required to access the data? Yes ☐ No ☒
If you answered no to question 1 and yes to questions 2 or 3, your study does not need ethics approval and you will need to complete this form but not the other ethics documentation.	

Filter for ICREC and SETREC	Is the primary aim of the research answering a human health related question? Yes ☐ No ☒ Is the primary aim of the research answering a non-health related science, social science, engineering or technology related question? Yes ☒ No ☐ Is the primary aim of the research to answer an educational question? Yes ☐ No ☒
If you answered yes to question 3 your ethics application needs to be submitted to the Education Ethics Review Process (EERP) using their forms. https://www.imperial.ac.uk/research-and-innovation/support-for-staff/education-ethics/how-to-apply/	

Risk level categorisation This section determines the research risk level and if the application requires full committee review.	Does the research involve drugs/medication? *If yes, please attach the SmPc.* Yes ☐ No ☒ Does the research involve genetically modified materials? *If yes, please also complete appendix two and attach the GM Safety Committee letter.* Yes ☐ No ☒ Will you be recruiting vulnerable participants? i.e. children (15 years or younger), adults (16 years or over) who are unable to consent, people in care, the mentally ill or individuals with learning difficulties? Yes ☐ No ☒ Will participants take part in the study without their explicit consent? i.e. studies involving deception. Yes ☐ No ☒ Will you be recruiting prisoners or young offenders? Yes ☐ No ☒ Is there any aspect of the proposed research which could potentially cause harm to the reputation of the College? i.e. could the research be considered controversial or prejudiced? Yes ☐ No ☒ Could participants disclose any illegal or harmful activity due to the nature of the research? Yes ☐ No ☒ Will personally sensitive subjects be discussed that have the potential to induce stress, anxiety or negative consequences for the participant? Yes ☐ No ☒

	Will the researcher be in a position of influence or authority over the participants that could give rise to a perceived pressure to participate? i.e. lecturers/teachers and students. Yes ☐ No ☒

Section 4: Continued Risk level categorisation This section determines the research risk level and if the application requires full committee review. Meeting dates and submission deadlines ICREC/SETREC.	Does the study involve physically intrusive procedures, administration of substances, use of bodily fluids, tissues, DNA or RNA? ***Use of relevant material must be registered with Imperial College Tissue Bank under the College HTA license.*** Yes ☐ No ☒ Does the study involve ultrasound or sources of non-ionizing radiation? i.e. radiation, MRI, or fMRI. Yes ☐ No ☒ Are there any potential conflicts of interest, or what could be perceived by an outside observer as conflicts of interest? Yes ☐ No ☒ Will undue incentives for participants be offered? Incentives should be proportionate to the burden imposed and justified by the benefits. Yes ☐ No ☒ Are you using any medical device in the UK that is CE/UKCA marked but is being used outside its product limitation? Or are you using any non-CE/non-UKCA marked product(s)? *For more information on regulating medical devices.* Yes ☐ No ☒ Does the proposed research raise any ethical issues that are not covered above? Yes ☐ No ☒
If you answered YES TO ANY of the questions a) to o), your study is considered high risk and you must complete the entire application, parts 2, 3 and 4 of this form. If you answered NO TO ALL the questions above, your study is considered low risk. Complete parts 2 and 4, skipping part 3.	

Part 2 (to be completed by all)

Project Description	
Full title of study	What are the investment and operational costs of Na-Zn molten salt batteries and how cost competitive will they be against other
P code or cost code and study funder (only if applicable to study)	Not applicable
Lead organisation (who has overall responsibility for the study)	Imperial College London
List of location(s) where study will be conducted	London
Proposed start date *From start of advertising*	7th June 2021
Proposed end date *To end of data collection*	31st August 2021

Project Summary
Provide a summary of the project in **lay terms**: a brief description of reasons for doing the study, the aims, how data will be disseminated and any expected benefits to the participant, researchers or others. *(500 words max)*
Energy storage systems can be used to capture excess energy and store it to be used later when it is needed within an electrical power grid. As global grids make a transition to a clean energy system in line with the Paris Agreement, large scale deployment of energy storage systems is one of the key options to cope with the increased reliance on intermittent renewables. Pumped hydro is currently the main energy storage system and makes up approximately 98% of the global energy storage capacity. However, battery storage can provide many advantages over pumped hydro such as an almost immediate response time, faster construction time, higher round-trip efficiency, greater energy density, more location flexibility and the potential for lower costs/kWh.

Currently lithium-ion (Li-ion) batteries are the most used battery energy storage system. However, Na-Zn molten salt batteries have the potential for a lower environmental impact with better performance characteristics at a lower cost than lithium-ion batteries due to the high abundance of sodium and zinc and the simple design of a molten salt battery. These characteristics could make Na-Zn molten salt batteries the necessary technology for low-cost, large scale energy storage to aid the transition to a 100% renewable energy-based power system heavily reliant on intermittent wind and solar power.

I will be investigating what the investment and operational costs of Na-Zn molten salt batteries are, and how cost competitive the technology is against other technologies in the future.

This will be tackled by creating an engineering cost model built in Excel and will include all the cost components of the battery system (including the materials, manufacturing and balance-of-system). The necessary input parameters (such as materials and volumes) and battery characteristics (such as voltage and current) for the engineering cost model will be collected via secondary data. The engineering cost model will then be scoped and later refined by interviews with the 12 partners involved in the SOLSTICE project.

This project is part of an EU Horizon 2020 project with 12 research partners across Europe. It will involve interaction with these partners and participation in joint workshops.

Research Methods
What methods will you be using in this study? Briefly describe in lay terms: what will happen, the number of times and any data collection techniques. *(500 words max)*
This research project requires a variety of research methods composed of the following methods: Desk research and literature review:

By conducting desk research and writing a literature review I expect to understand the technology, including the design and materials necessary to build a Na-Zn molten salt battery and the characteristics of the battery. This secondary data will allow me to collect the necessary input data for the engineering cost model. Furthermore, by conducting desk research on other engineering cost models such as the BatPac model I will understand how to build an engineering cost model and the necessary data and calculations I will need to estimate the investment and operational costs of Na-Zn molten salt batteries.

Up to 10 semi-structured interviews with the 12 research partners involved in the SOLSTICE project:
By conducting expert interviews, it will help me collect the most up to date and expert information of this novel battery technology. After conducting desk research I will organise several interviews to portray my vision for the project, projected methods, key inputs and structure of the engineering cost model to gain expert guidance on how to scope the project before building the model. Then after building the model with the collected secondary data from desk research, I will conduct more interviews with the research partners to refine the model, input parameters (eg materials and volumes) and battery characteristics (eg voltage and current). I also expect that these expert interviews will help me collect relevant information that is not publicly available.

Building an engineering cost model:
I will first understand how an engineering cost model is built by researching other engineering cost models such as the BatPac model. The bottom-up model will be a calculation method based on Microsoft Excel spreadsheets that will estimate the investment and operational costs of Na-Zn molten salt batteries. The model will incorporate the design of the battery necessary to meet the performance requirements (energy, power and recharge time), the cost of materials, the manufacturing process and projected economies of scale to estimate the total cost of the battery technology. These inputs will be collected from secondary data before being refined by information gained in expert interviews with the 12 research partners involved in the SOLSTICE project.

Monte Carlo Simulation:

I will couple the completed engineering cost model with the Monte Carlo method to automatise parameter space and help assess the range of possible total costs based on the uncertainties attributed to certain input parameters.

Present findings:

I will share insights and my findings from the engineering cost model with the 12 research partners, through a presentation at a project team conference, to gain expert knowledge and feedback to improve my model and make any necessary changes to ensure our visions for the project align.

Participant Recruitment

Provide details of methods of recruitment, participant inclusion and exclusion criteria and the number of participants you are aiming to recruit. Include details of any incentives (such as financial reimbursement). *(500 words max)*

Attach as separate documents (if applicable):

- Recruitment and advertising material (email, poster, social media advert)
- Oral information scripts

For this research project semi-structured interviews will be conducted with members from the 12 research partners involved in the SOLSTICE project. The study requires expert insights from the partners working on the novel Na-Zn molten salt battery technology so I can scope and refine my engineering cost model with the most up to date and expert analysis.

Details of the methods of recruitment are as follows:

Using the connections my supervisors have with the 12 research partners involved in the project, potential participants will be identified and contacted by email.

Potential participants will also be identified via internet search and contacted by email

Participant inclusion criteria: Experts working for any of the 12 research partners involved in the SOLSTICE project

Number of participants: 8-12

No incentives will be provided to the participants

Informed Consent

Include details of how you will be obtaining consent.

i. Detail the process for ensuring informed consent of all research participants.

ii. The withdrawal process(es).

iii. If vulnerable persons are to be used in the study, give separate specific information on how you will ensure consent.

iv. If participants whose first language is not English are to be recruited, state clearly how the details of the study will be explained, and the consent processed.

All of the research participants will be contacted by email with an overview of the interview including the scope of study and the type of questions being asked. They will then be asked individually if they are willing to be interviewed in the context of the study. An interview will take place only once the research participant agrees to be interviewed. At the start of the interview, the participants will be asked if they consent to the interview being recorded, the interview will not be recorded unless oral consent is received.

Each research participant who agrees to participate in the study via interview may withdraw from the project at any time until the full completion of the research project. Individuals can withdraw by contacting Ross Berridge via email or orally either during the interviews or over the phone. If the interview has already been completed at the time of the participant withdrawal, the participant can either choose to have all data collected during the interview anonymised, or removed from the study and deleted.

No vulnerable people will be used in this research project.

The project will be recruiting participants who are fluent in English to negate any issues around explaining the study and gaining consent.

Ethical Summary

Has any part of this proposal received prior ethics approval?

Yes ☐ No ☒

Is this study subject to local ethics approval?

Yes ☐ No ☒

If yes, list all local approvals required.

If yes or if rejected, please give details and attach any relevant documents.

(150 words max)

Provide details of what you consider to be the ethical issues surrounding this project: your own physical safety, COVID-19 safety measures, data protection/ confidentiality and how you have addressed this. Include details if you will inform participants of the results. If the study is of a sensitive nature include information regarding signposting to relevant support groups.

If you answered yes to any questions in section 3, please provide specific information on those ethical issues and how they will be mitigated. Detail any PPI undertaken as part of study set up or design.

(500 words max)

This will be a desk-based study with interviews being conducted through online meetings (via Skype, Teams, Zoom etc). This will ensure there are no issues with physical safety and COVID-19.

Data protection and confidentiality will be assured through emailing participants an overview of the scope of study and nature of the questions to be asked. I will then only conduct the interviews if I get consent to do so. The interviewees will be asked if they consent to being recorded during the interview and if they wish for their name or position to be included in the research project and will only be included if they consent to it. I will not use any collected data without the consent of the participants.

Once the interview has commenced and before the data is processed, I will email the participants an electronic summary of the interview. The participant will then be able to freely edit the content. I will only use the data collected with the consent of the participant.

Once the study has commenced in early September participants of the study will be offered to receive an electronic copy of the final research project via email.

Documentation checklist Mark as either Yes/ No/ In process	Do Imperial College' insurers need to be notified about your project? If your project is running abroad and is not qualitative or data only, or if your project is interventional and involves pregnant women, children under 5 or more than 5000 participants you may need additional insurance cover. Insurance for studies, email the insurance team with any insurance enquiries. *If yes, please provide confirmation that insurance cover has been agreed.* Yes ☐ No ☒ In process ☐ Has your research project been independently peer reviewed? This can be organised by the Peer Review Office (within the RGIT). If you answered yes to any questions in section 3, you may be asked to ensure the study is peer reviewed. However, the study does not have to use the RGIT's office for peer review. Yes ☐ No ☒ In process ☐ Are you developing a mobile app? See the mobile app webpage for more information. Yes ☐ No ☒ In process ☐ Have you had a Disclosure and Barring Service (DBS) check carried out? If yes, when (add date). For more information about DBS, check government guidance and the College website. Yes ☐ No ☒ In process ☐ Do you need a contractual agreement in place? For further information, please contact your faculty research service. Yes ☐ No ☒ In process ☐ Do you have permissions to use the data in your study? This may be required if you are looking at secondary data. Yes ☒ No ☐ In process ☐ Has Imperial College's Risk Assessment procedure been followed? Contact your departmental administrator for further information. Yes ☒ No ☐ In process ☐

Confidentiality and management of personal and other research data	I understand it is the responsibility of the researcher to ensure all research data is securely stored during and after the study in accordance with College Guidelines, Codes of Practice, Policies and Procedures. Yes ☒ No ☐ I confirm that all the processing of personal information related to the study will be in full compliance with the GDPR. Including but not limited to, the creation of all necessary documentation (PIS, Data Protection Impact Assessments, Consent forms etc.) Yes ☒ No ☐

Part 3 (only to be completed if *yes* was answered to any question in section 4)

Mitigation of Risks and Safeguarding
Explain the precautions taken to protect the health and safety of researchers, participants and others associated with the project. You need to safeguard the wellbeing and safety of children and adults at risk involved in research activities. Safeguarding means taking all reasonable steps to prevent harm, exploitation, and abuse from occurring; protecting people, especially adults 'at risk' and children, from that harm; and responding appropriately when harm does occur. Explain what information you have on the potential harms this research can address or exacerbate for researchers, participants and wider communities. Explain how you are building the rights of potential or actual victims/ survivors of safeguarding incidents into the research design, including questions and methodology, to ensure respect, dignity and safety. Visit the website for more information on safeguarding for research. *(500 words max)*
Not applicable.

I will ensure that access to (community-based – for studies outside of the UK) complaint mechanisms to raise safeguarding concerns are built into the programme design and are discussed and explained with participants.

Yes ☐ No ☐

I am willing to modify or even cancel planned research if potential harm to researchers, participants or communities is too great.

Yes ☐ No ☐

I will ensure that we and our research partners reach a shared understanding of safeguarding

Yes ☐ No ☐

Part 4 (to be completed by all)

Co-investigators/ Collaborators	
If there are more than four co-investigators, please use a separate sheet and follow the format below.	
Name	Ross Berridge
Position *Incl. organisation, company, institution*	Postgraduate Student, MSc Environmental Technology, Imperial College London
Role in the study *(what contributions you will make and relevant experience)*	Conduct the entire research, including the interviews with the research participants.
Email *Work not personal*	ross.berridge17@imperial.ac.uk

Name	Dr. Oliver Schmidt
Position *Incl. organisation, company, institution*	Faculty of Natural Sciences, Centre for Environmental Policy. Visiting Researcher, Imperial College London.
Role in the study *(what contributions you will make and relevant experience)*	Supervision of Ross Berridge's work
Email *Work not personal*	o.schmidt15@imperial.ac.uk

Name	Iain Staffell
Position *Incl. organisation, company, institution*	Senior Lecturer, Imperial College
Role in the study *(what contributions you will make and relevant experience)*	PI
Email *Work not personal*	i.staffell@imperial.ac.uk

Name	
Position	

Incl. organisation, company, institution	
Role in the study *(what contributions you will make and relevant experience)*	
Email *Work not personal*	

Signatures Page - PI Declaration

I declare that:

I undertake to abide by the ethical principles underlying the Declaration of Helsinki (1964) and subsequent amendments and good practice guidelines on the proper conduct of research.

I undertake to abide by the Data Protection Act 2018 and General Data Protection Regulation (Europe) and any applicable local laws.

I undertake to abide by all local laws and regulations for non-UK research.

I will report any adverse or unforeseen events or protocol violations and deviations which occur to the Ethics and Research Governance Co-ordinator within 24 hours.

I will provide an annual progress report of the project until the end of the study.

If I register my study on a public database, i.e. ClinicalTrials.gov, I will report results on that database within one year of study completion.

I will provide notification of the end or early termination of the research project.

I will provide notification of amendment to ICREC/SETREC if there are any changes to the research protocol or personnel which affect the ethical aspects of the project.

I will assist ICREC/SETREC in any continuing review of the project deemed necessary by the Committee or Faculty Members.

All information on this form is correct.

PI Name	Dr. Iain Staffell	
PI Signature		Date 25/05/2021
If full committee review is required would you be willing to attend the ICREC/SETREC meeting to answer any questions about your proposal?		Yes

Any attendance must be by the PI named in section four. Attendance at the meeting will give you the opportunity to answer any ethics questions raised by the committee.

Head of Department *(please indicate below your decision and the reasons for it)*			
Decision		Referral to Committee	
Reason			
Signature		Date	
Name			

Appendix B – Table of Individual Cost Components

Cost Components	**$/cell**	**$/battery**	**$/kWh**
Cell components			
Cell cap	0.01	3.54	0.19
Flange for manifold	0.07	17.67	0.96
Positive current collector	0.54	129.87	7.04
Carbon felt	0.02	5.78	0.31
Bridging-piece	0.08	19.44	1.05
Outer Nickel	0.03	6.54	0.35
Sealing ring for TCB	0.02	3.75	0.20
Inner Nickel	0.05	11.41	0.62
Ceramic tube/electrolyte	0.17	41.83	2.27
Internal spring	0.10	24.65	1.34
Negative current collector/cell tube	1.07	255.69	13.86
Cell bottom closure	0.08	18.10	0.98
Zn	0.46	110.39	5.99
NaCl	0.03	6.13	0.33
Electrode additives	0.01	1.58	0.09
Secondary electrolyte	0.86	206.50	11.20
Joining material	0.01	1.62	0.09
BoS Components			
Electrical insulation	0.03	6.90	0.37
Thermal insulation	0.39	93.75	5.08
Battery case	0.24	57.60	3.12
Steel cooling system	0.05	11.25	0.61
Battery controller	1.04	250.00	13.55

Assembly costs			
Cell assembly cost	1.54	370.50	20.09
Battery assembly cost	1.75	419.50	22.75
Energy costs			
Total energy cost	0.13	31.35	*1.70*