Technology Roadmapping for Energy Storage using ZEBRA Batteries

by

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Abstract

Energy Storage Systems are expected to be the key enablers that will allow Variable Renewable Energy to increase its penetration in the electricity market. The objective of this thesis is to explore the application of ZEBRA Battery technology for Energy Storage Systems. The ZEBRA battery is of particular interest because it is a rechargeable battery built with Earth-abundant materials, primarily nickel and conventional table salt. Also, it has many advantages compared to Lithium Ion Batteries, such as lower degradation rates, higher safety performance, wider temperature range of operation, and less maintenance. To understand the role of batteries in hybrid energy systems, successful examples of electro-chemical Energy Storage Systems are discussed, and an analysis of the stakeholders is performed. Additionally, three different locations were studied: Maine, Texas, and Guinea-Bissau. A Design of Experiments approach was implemented to explore different solutions to supply the electricity demand with Variable Renewable Energy in these locations. A model was built to calculate the energy supply and the cost of it for each solution. Cases on the Pareto frontier were selected and analyzed to understand the performance of batteries. Finally, a Life Cycle Analysis of the system, a comparison with Lithium Ion Batteries, and a sensitivity analysis were performed. The main outcome of this work is a technology roadmap for ZEBRA batteries technology that will enable the adoption of this technology for Energy Storage Systems application by reducing its high capital cost. Currently, ZEBRA batteries exhibit a cost of about 600 USD/kWh. By applying the proposed projects, the cost of the battery is projected to be about 360 USD/kWh by the end of 2035.

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List of Acronyms

BMS Battery Management System. 42, 49, 50, 62, 64

CEO Chief Executive Officer. 34

DC Direct current. 49

DOD Depth of Discharge. 46, 47, 96

DOE Design of Experiments. 3, 8, 69, 78

DRC Democratic Republic of the Congo. 31

DSM Design Structure Matrix. 7, 12, 41

EDM Entrepreneurs du Monde. 74

ERCOT Electric Reliability Council of Texas. 92

ESS Energy Storage Systems. 3, 7, 8, 11, 12, 21, 23, 24, 25, 26, 27, 33, 35, 46, 47, 49, 52, 53, 54, 69, 98, 99, 102, 106, 109, 110, 111

EU European Union. 52, 65

EVs Electric Vehicles. 11, 33, 34, 56, 63, 64, 65

FI Flammability Index. 48

FOM Figure of Merit. 7, 45, 48, 52, 53, 60, 111

FOMs Figures of Merit. 7, 15, 42, 45, 46, 48, 52, 53, 100, 103, 107, 111

FPMs Functional Performance Metrics. 46

GE General Electric. 35, 65, 69

IRR Internal Rate of Return. 58, 99, 100, 104, 107

LCA Life Cycle Analysis. 3, 8, 69, 95, 97, 101, 104

LCO Lithium Cobalt Oxide. 29

LCOE Levelized Cost of Electricity. 81

LCOS Levelized Cost of Storage. 46, 81, 95

LFP Lithium Iron Phosphate. 29, 34, 55

LIB Lithium Ion Battery. 21, 29, 47, 56, 65, 69, 72, 95

LIBs Lithium Ion Batteries. 3, 7, 8, 15, 25, 28, 29, 31, 33, 34, 35, 47, 49, 53, 56, 60, 72, 73, 95, 96, 98, 100, 102, 103, 105, 106, 111

LMO Lithium Manganese Oxide. 29

MIT Massachusetts Institute of Technology. 48, 112

MRL Manufacturing Readiness Level. 112

NCA Lithium Nickel Cobalt Aluminium. 29

NMC Lithium Nickel Manganese Cobalt Oxide. 29, 33, 55, 95

NPV Net Present Value. 8, 12, 13, 14, 57, 58, 59, 60, 99, 100, 102, 103, 104, 106, 108, 111

O&M Operations and Maintenance. 48, 49, 96, 111

OPD Object Process Diagram. 11, 12, 28, 36, 42, 43, 44, 45, 50, 51, 71, 74

OPL Object Process Language. 14, 28, 36, 42, 43, 50, 71, 74, 123, 125, 126, 127, 128, 129, 130, 131

OPM Object Process Methodology. 28

PHS Pumped Hydro Storage. 21, 24, 25, 70

PPM Parts per million. 48

R&D Research and Development. 35

R&T Research and Technology Development. 8, 12, 41, 57, 58, 59, 60, 67, 109

RTE Round-Trip Efficiency. 28, 46, 55, 110

SDG Sustainable Development Goal. 22

SOC State of Charge. 13, 14, 97, 98, 101, 104, 105

SOH State of Health. 95, 96

SPS System Problem Statement. 11, 14, 36, 124

SVN Stakeholder Value Network. 13, 76

TRL Technology Readiness Level. 112

UBEM Urban Building Energy Model. 79

UN United Nations. 22

UNICEF United Nations Children's Emergency Fund. 31

UPS Uninterruptible Power Supply. 35, 55

US United States. 64, 65

VRE Variable Renewable Energy. 3, 7, 21, 23, 25, 47, 69, 95, 97, 104, 109

Chapter 1

Introduction

Energy Storage Systems (ESS) will be critical enablers for increasing the penetration of Variable Renewable Energy (VRE) in the electric market. VRE demand will increase significantly in the upcoming years as countries are trying to decarbonize their economy or meet new electricity demand in the developing world with affordable and sustainable energy. Most of the ESS projects are Pumped Hydro Storage (PHS). The second most important category is Electrochemical ESS (batteries) projects, continuously growing over the last decade. The leading technology in this category is state-of-the-art Lithium Ion Battery (LIB) technology, but the use of this technology raises concerns about the future availability and cost of its raw materials and the environmental and ethical issues along its supply chain. For that reason, ZEBRA battery technology is introduced as an alternative.

1.1 Current Context of Variable Renewable Energy

ESS will enable VRE, like wind and solar energy, to increase its participation in the electric market by bridging the mismatch of power supply and power demand (IEA, 2014). The role of ESS will become more critical in the upcoming years. Many countries are increasing their VRE share in energy consumption to fulfill their decarbonization targets and comply with international agreements such as the Paris Agreement (*The Paris Agreement*, n.d.), as shown in figure Figure 1-1. Other countries are facing the challenge of providing their population with energy to fulfill the United Nations (UN) Sustainable Development Goal (SDG) #7, as shown in Figure 1-2. The purpose of the SDG #7 is to "ensure access to affordable, reliable, sustainable and modern energy for all" (*Goal 7*, n.d.).

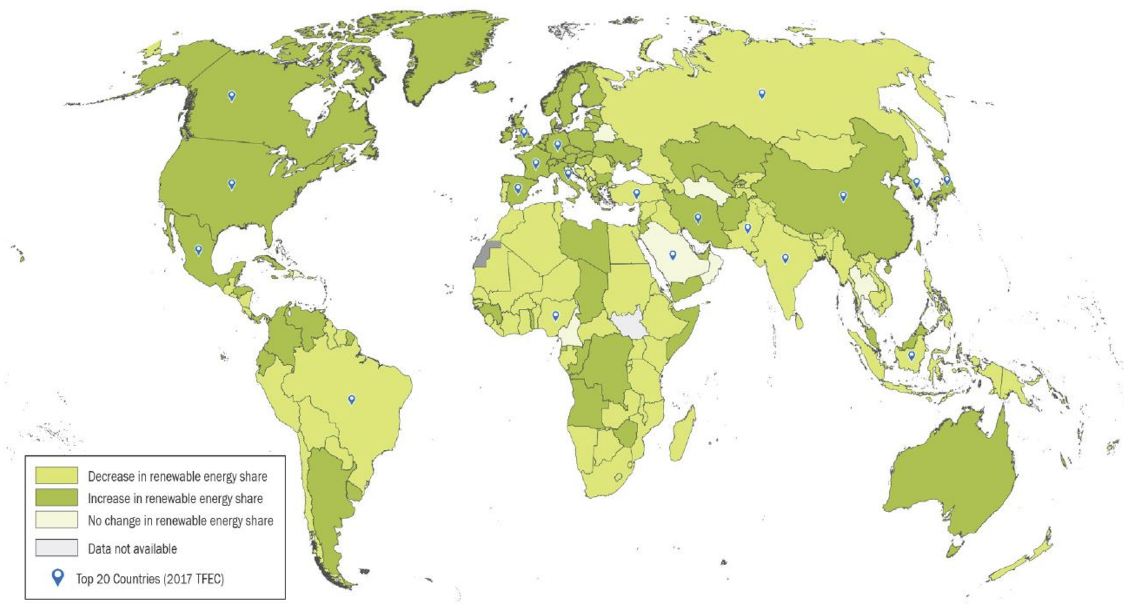


Figure 1-1: Change in share of renewable energy in total final energy consumption between 2010 and 2017. Source: IEA et al. (2020).

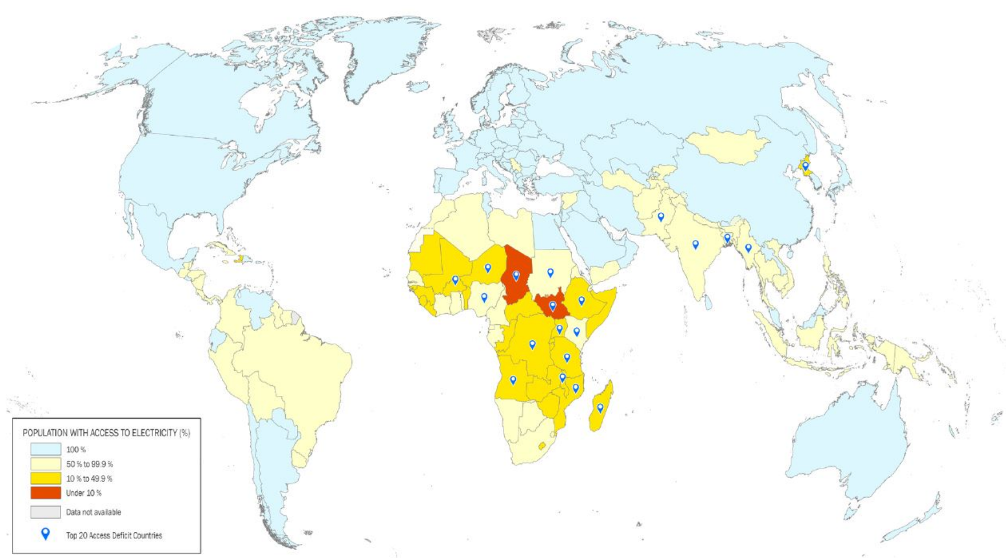


Figure 1-2: Share of population with access to electricity in 2019. Source: IEA et al. (2021).

According to *Renewables | Energy economics | Home* (n.d.), the VRE participation in the power sector globally will increase significantly by 2050, as it can be seen in Figure 1-3. Three scenarios were explored by 2050. In the "Business-as-usual" scenario, the energy from renewable sources will be 6.6 times its amount in 2018. In the "Rapid" scenario, the energy from renewable sources will be 11.4 times its amount in 2018. Finally, in the "Net-Zero" scenario, the energy from renewable sources will be 15.3 times its amount in 2018.

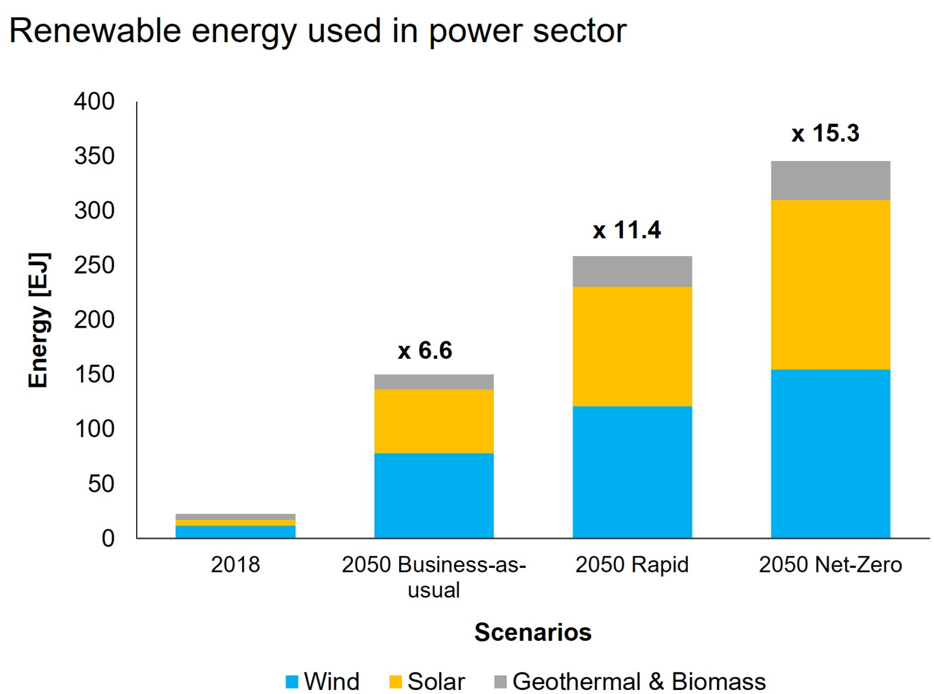


Figure 1-3: Renewable energy used in power sector. Source: *Renewables | Energy economics | Home* (n.d.).

1.2 Energy Storage Systems

Figure 1-4 shows a Tradespace where it is possible to see the ranges of application for different ESSs. The range for batteries is highlighted in red, as the main object of this study belongs to this group. Two arrows in red indicate the challenges that batteries face for their applications for Energy Grid Storage projects.

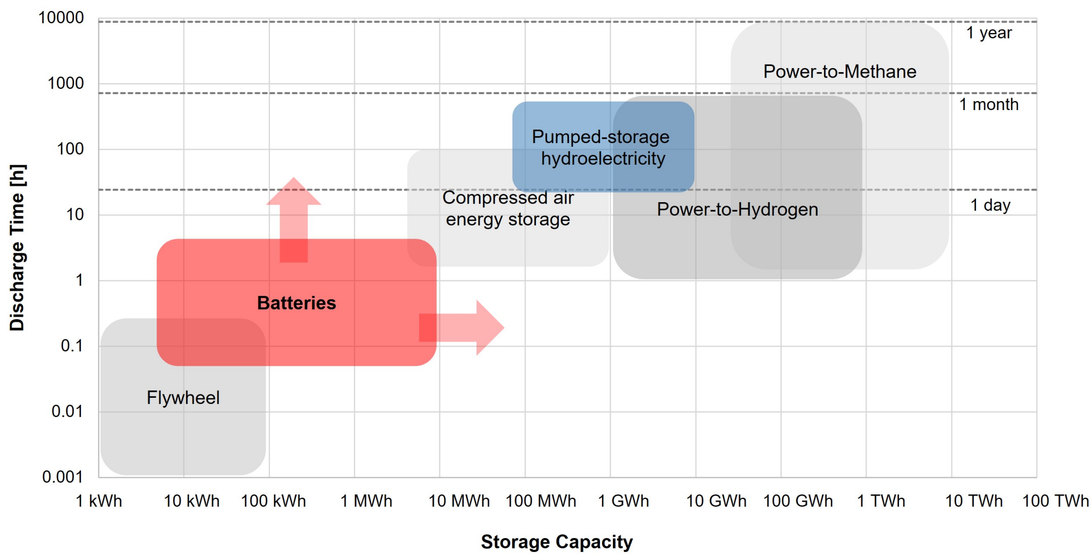


Figure 1-4: ESS Tradespace. Adapted from: Moore & Shabani (2016).

According to *Global Energy Storage Projects Database* (2020) there were more than 1600 energy storage projects worldwide by November 2020. As it is possible to see in Figure 1-5, PHS technology is used in almost 95% of the Energy Grid Storage projects worldwide. In contrast, only 2.2% of Energy Grid Storage projects utilize Electrochemical Energy Storage technology, i.e. batteries.

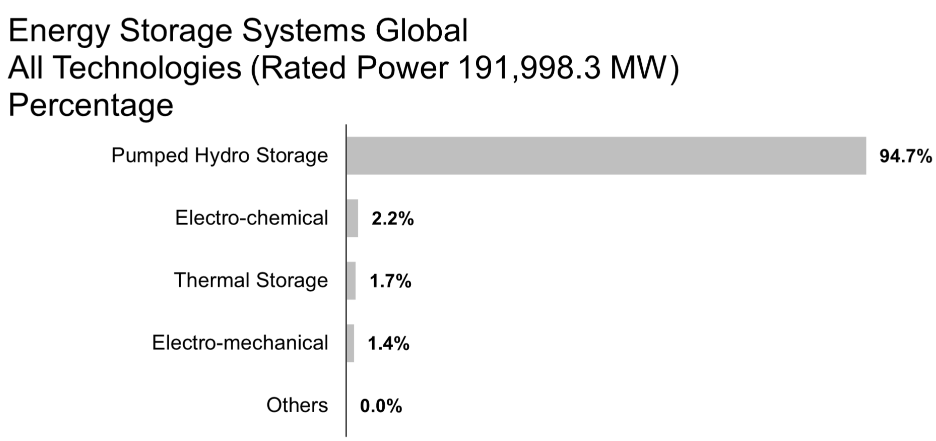


Figure 1-5: Global ESS. Source: *Global Energy Storage Projects Database* (2020).

Even though PHS is the technology that leads Energy Storage projects, it is only suitable for projects under some specific conditions such as:

- Capital-intensive projects (Foley et al., 2015).
- Access to an electric grid that connects VRE sources with consumers (Blakers et al., 2021).
- Access to water (close to a river, sea, etc.).
- A big area for a water reservoir in specific topographic conditions that allow storing energy at a certain height (potential energy).

For those projects that cannot fulfill these requirements, Electrochemical Energy Storage is the next best option. The breakdown of the projects that use Electrochemical Energy Storage technology can be seen in Figure 1-6. As it can be observed, LIBs account for 72.8% of those projects, being the leading technology in this category. Sodium-based batteries currently account for 5.3%, including Sodium-ion batteries, Sodium-Sulfur batteries, and Sodium-Nickel-Chloride batteries, also known as ZEBRA batteries.

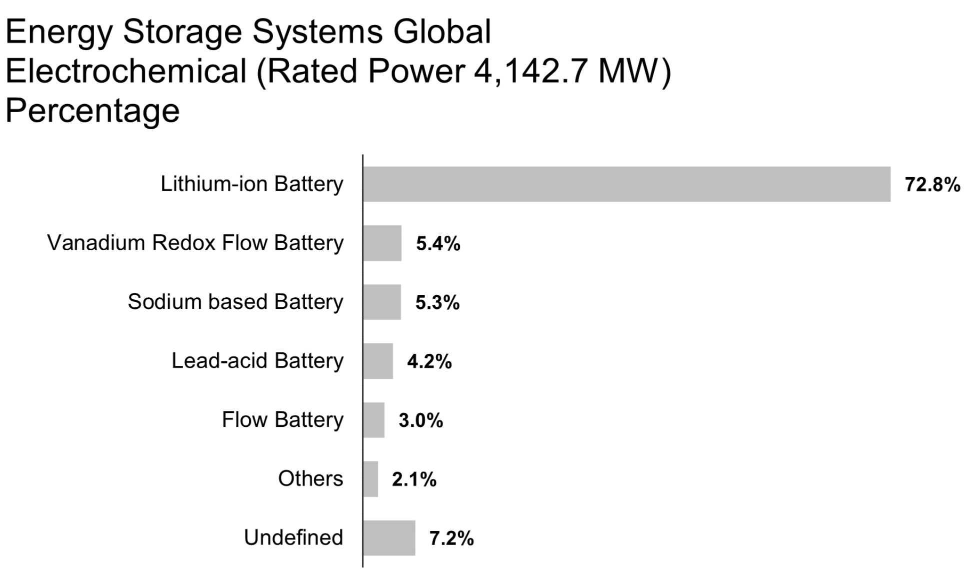


Figure 1-6: Global ESS with Electrochemical technologies by type. Source: *Global Energy Storage Projects Database* (2020).

In Figure 1-7 a cumulative rated power curve is shown for those Electrochemical ESS projects in the database with information about the construction or commissioning date. Here, an exponential increase in the number of projects can be noted in the last decade.

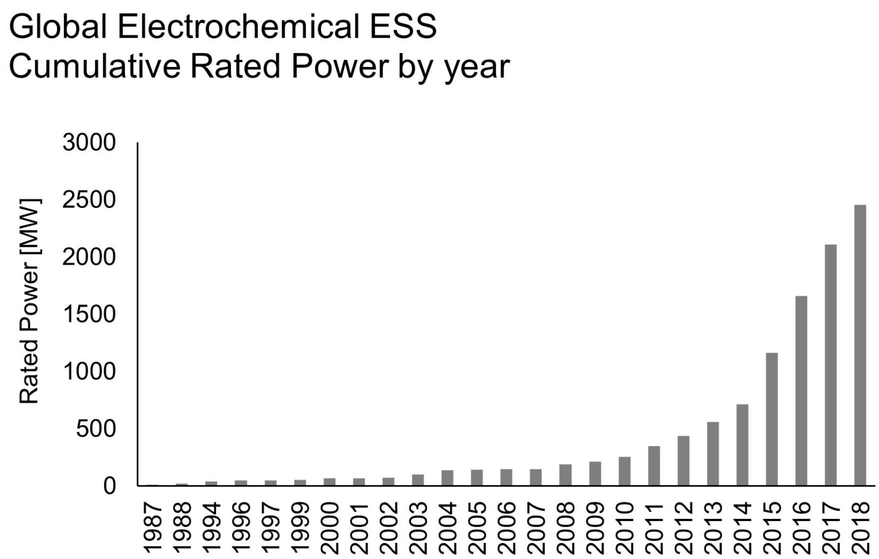


Figure 1-7: Cumulative Rated Power by year for Global ESS with Electrochemical technologies. Source: *Global Energy Storage Projects Database* (2020).

The first Electrochemical ESS project above 100 MW was finished in 2017. Since then, it took three years for projects of 200-300 MW to be developed. Projects of 400 MW and above have been announced and are expected to be in operation by 2025. It is interesting to see that these projects would be outside of the red area highlighted in the tradespace in Figure 1-4, as the source (Moore & Shabani, 2016) is from 2016. Big projects are more economically feasible than in the past because ESS prices, which have been decreasing consistently, are inversely proportional to the size of the projects (Longson, 2021). A forecast of the Electrochemical ESS installations per year by segment can be seen in Figure 1-8.

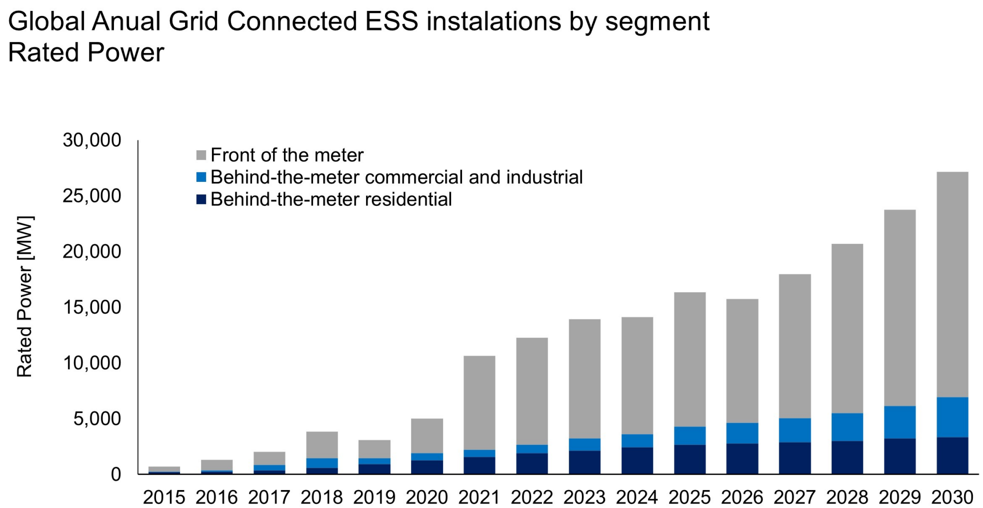


Figure 1-8: Rated Power of Global Annual Grid Connected Electrochemical ESS installations by segment. Source: Longson (2021).

1.3 Batteries

Batteries must be considered as a system within a bigger system that is the whole ESS, as it can be seen in Figure 1-9.

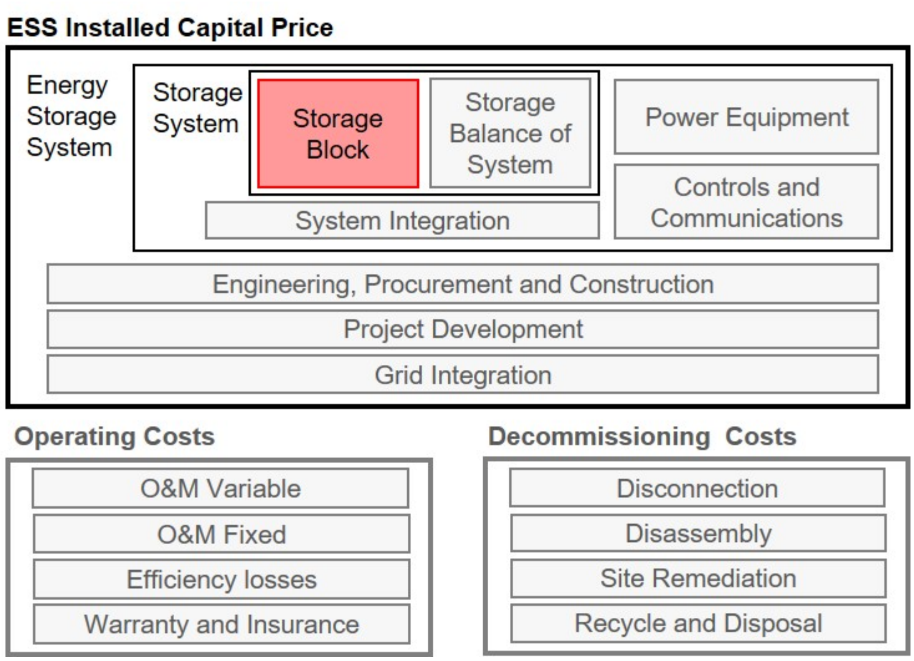


Figure 1-9: ESS price decomposition. Adapted from: Mongird et al. (2020)

Utilizing the Object Process Methodology (OPM), the energy storage family for Batteries can be seen in an OPD in Figure 1-10 and its corresponding Object Process Language (OPL) in Figure B-1.

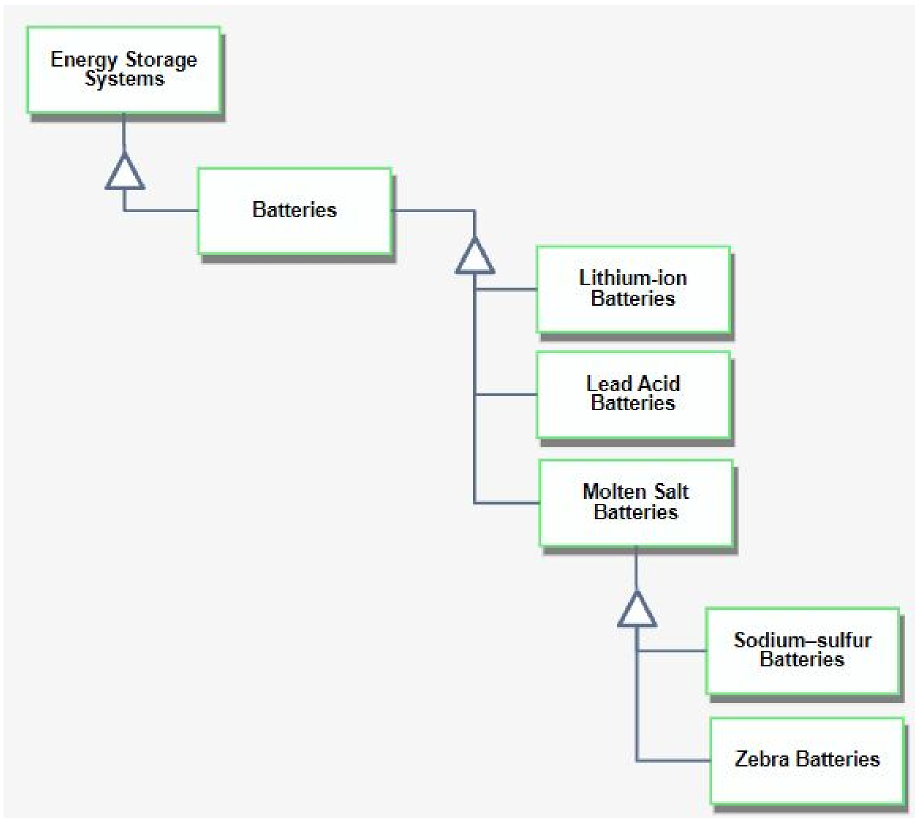


Figure 1-10: Energy Storage Family for ZEBRA Battery OPD.

1.3.1 Lithium Ion Batteries

LIBs History

The history of LIBs dates from the 1980s and it has been widely utilized in portable electronics since then. LIBs technology is characterized by high RTE, high energy and power density, and a low self-discharge rate. Its high power density has made it suitable for powering electric vehicles (Ding et al., 2015). Recently, the first efforts to extend its applications to energy storage projects have been carried out as the examples developed in section 3.1.1 aim to illustrate.

LIBs Materials

In general terms, LIB technologies require three minerals: Lithium, Cobalt and Nickel. The main LIB technologies are:

- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Cobalt Oxide (LCO)
- Lithium Nickel Cobalt Aluminium (NCA)
- Lithium Manganese Oxide (LMO)
- Lithium Iron Phosphate (LFP)

Lithium As illustrated by Figure 1-12 below, which shows the lithium mineral demand over time, LIBs have become the driver of the increasing lithium demand. According to recent industry reports, this type of battery corresponded to 41% of total lithium demand in 2017, and it is forecasted to surpass 76% by 2025 (Azevedo et al., 2018) .

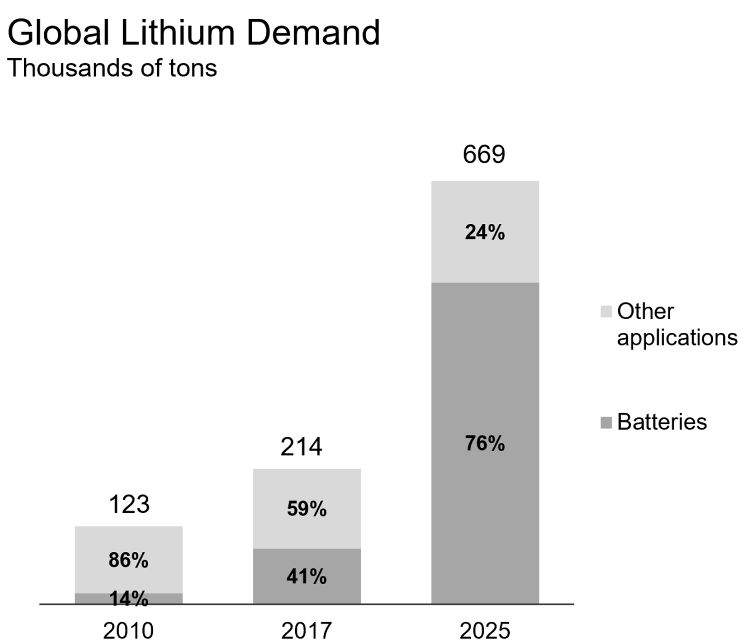
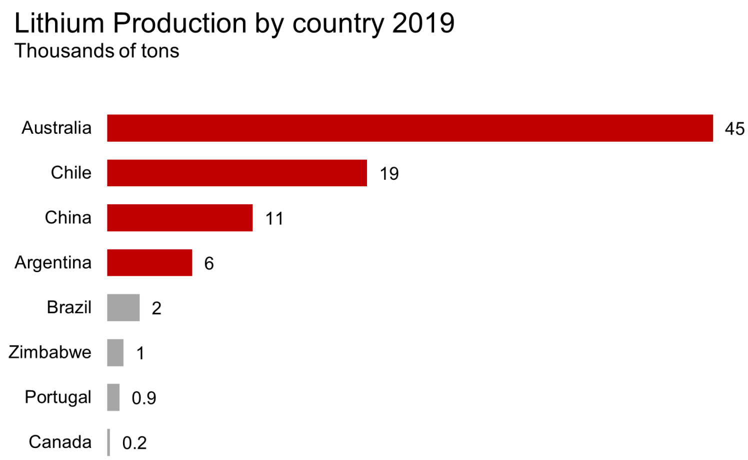
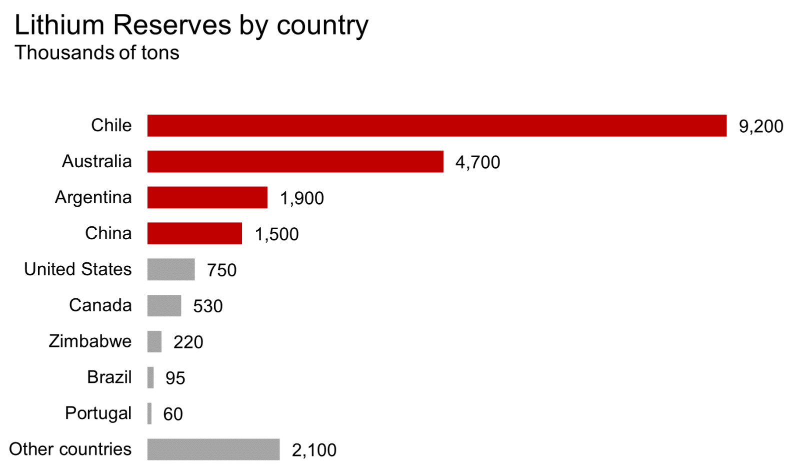


Figure 1-11: Lithium demand over time. Source: Azevedo et al. (2018).

As shown in Figure 1-12, the production and reserves of lithium are concentrated in four countries: Chile, Australia, China, and Argentina (highlighted in red). These countries together concentrate 94.5% of the world's lithium production and 82.2% of the lithium reserves in the world.



(a)



(b)

Figure 1-12: Lithium 2019 Production and Reserves by country. Source: *Mineral commodity summaries 2021* (2021)

Due to the high demand for this mineral, there is an increasing concern about the sustainability of the lithium mining activity. For example, in certain regions, the intensive use of water for the lithium brine evaporation method can lower the levels of the freshwater reservoirs that local communities require to meet their needs. Another example is that this activity can pollute the water streams of the surrounding areas

(Flexer et al., 2018; *The Environmental Impact of Lithium Batteries*, 2020).

Cobalt LIBs have become the driver of the increasing cobalt demand. According to recent industry reports, this type of battery corresponded to 30% of total cobalt demand in 2017, and it is forecasted to surpass 53% by 2025 (Azevedo et al., 2018). The cobalt mineral demand can be seen in Figure 1-13.

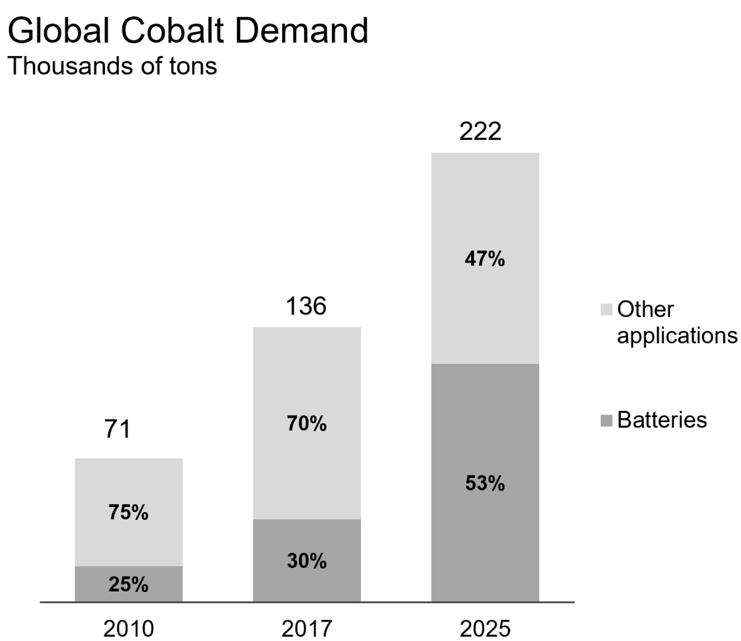
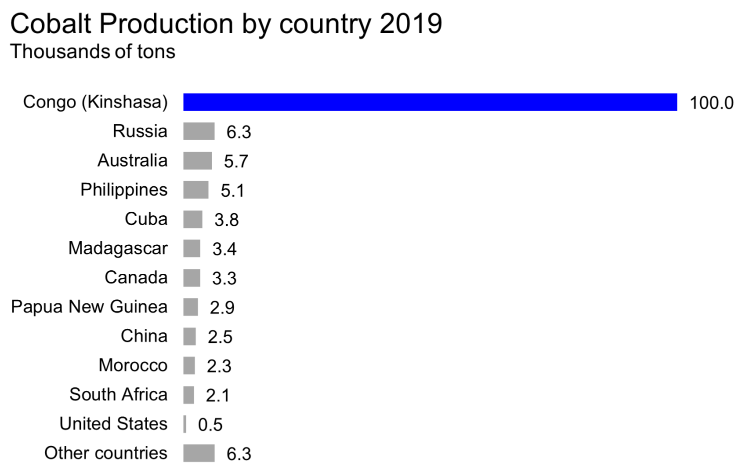
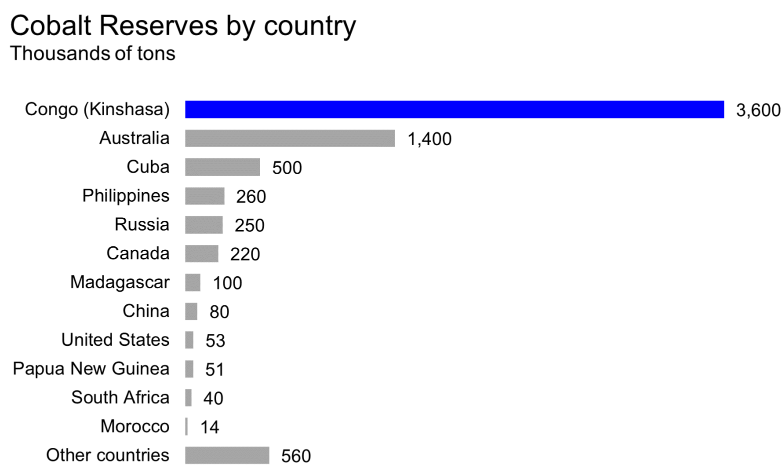


Figure 1-13: Cobalt demand over time. Source: Azevedo et al. (2018).

As shown in Figure 1-14, The Democratic Republic of the Congo (DRC) (highlighted in blue) concentrates 69.3% of the world's cobalt production and 50.5% of the cobalt reserves in the world. In the DRC, 20% of cobalt comes from artisanal mines where, according to United Nations Children's Emergency Fund (UNICEF), 40,000 children work in highly precarious conditions, which is a serious hazard to children's health (*Developing countries pay environmental cost of electric car batteries*, 2020). This fact is having a negative impact on the companies that demand that mineral (*Apple and Google named in US lawsuit over Congolese child cobalt mining deaths*, 2019).



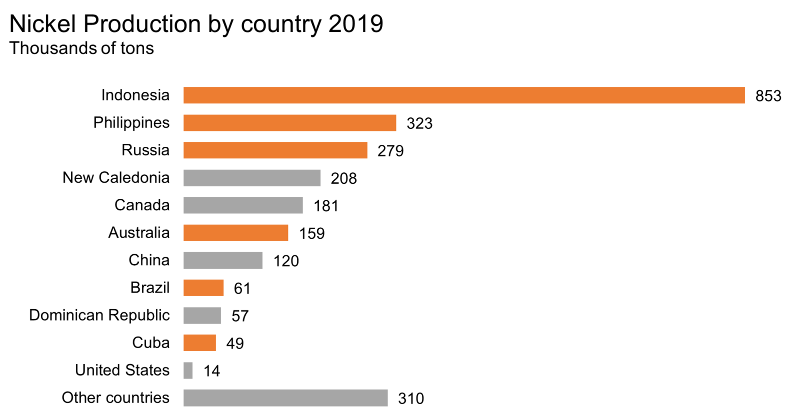
(a)



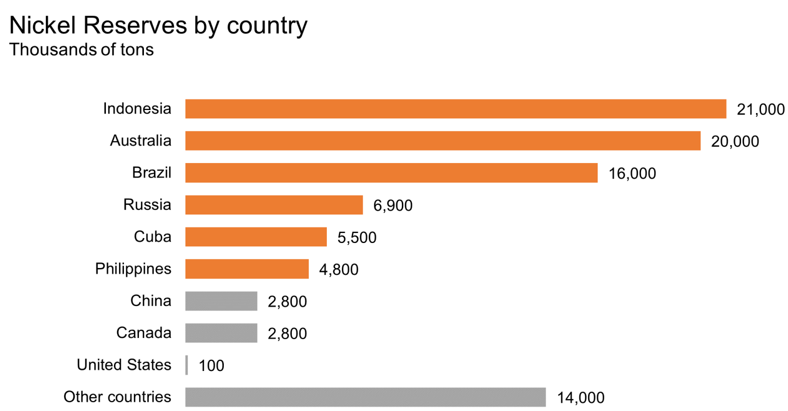
(b)

Figure 1-14: Cobalt 2019 Production and Reserves by country. Source: *Mineral commodity summaries 2021* (2021)

Nickel As shown in Figure 1-15, the production and reserves of nickel are concentrated in six countries: Philippines, Cuba, Russia, Brazil, Australia, and Indonesia (highlighted in orange). These countries together concentrate 87% of the world's nickel production and 79% of the nickel reserves in the world.



(a)



(b)

Figure 1-15: Nickel 2019 Production and Reserves by country. Source: *Mineral commodity summaries 2021* (2021)

Battery manufacturers will need strategies to secure nickel supplies to protect themselves from curtailments and price spikes. Partnerships between battery manufactures and miners may be a possible answer. For instance, Nornickel agreed to supply the nickel for BASF's prospective manufacturing plants of cathodes (Campagnol et al., 2017).

LIBs for ESS applications

Most of the Electrochemical ESS projects that utilize LIBs correspond to NMC batteries. This specific technology was developed for EVs. It may be hard to obtain the necessary high-quality LIBs with NMC technology for other applications than EVs, as its demand will increase significantly, which is shown in Figure 1-16, and the automotive industry can sign massive contracts to ensure supply. This rising demand will put pressure on the prices of the minerals covered in the previous section (Azevedo et al., 2018).

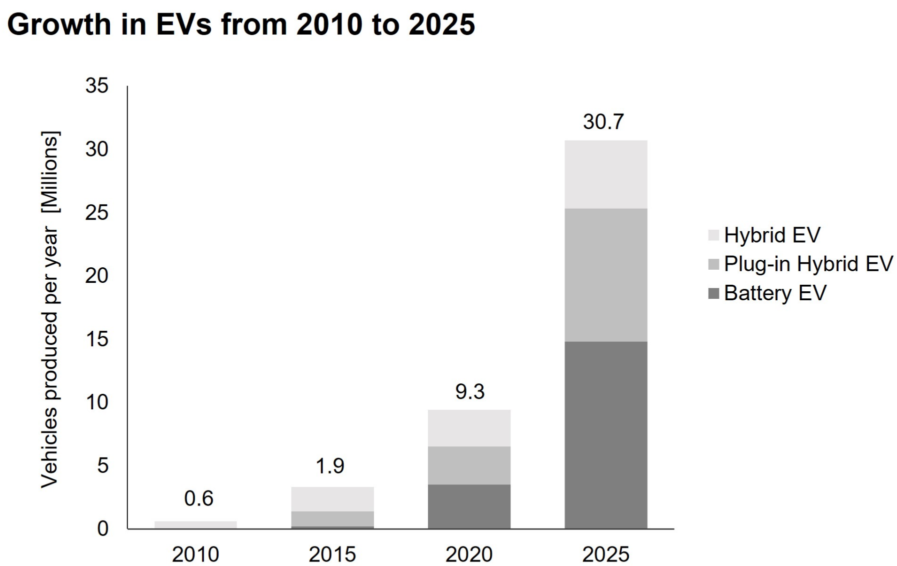


Figure 1-16: EVs demand over time. Source: Campagnol et al. (2017).

On February 25th 2021, Elon Musk, Chief Executive Officer (CEO) of Tesla, published a tweet saying, "Nickel is our biggest concern for scaling lithium-ion cell production. That's why we are shifting standard range cars to an iron cathode. Plenty of iron (and lithium)!" (Elon Musk, the 2nd, 2021). By stating this, the CEO of Tesla recognized the need for this mineral in the company's supply chain. The iron cathode technology corresponds to the LFP battery. After that statement, Tesla became an industrial adviser at the Goro mine, a large nickel mine in the south of New Caledonia owned by the Brazilian company Vale. This is a way to ensure nickel supply for Tesla LIBs production for EVs (Duffy, 2021). In addition, multiple sources have stated that Tesla will be using LFP battery cells in its "Megapack," its largest battery product (3 MWh per unit) for utility-scale energy storage. Therefore, the use of LFP technology would decrease the price of this product (Hanley, 2021).

1.3.2 ZEBRA Battery

ZEBRA battery technology is the object of study of this thesis. It is introduced as a competitor for the LIBs for ESS projects. Its technology roadmap will be developed in Chapter 2 and its applications will be studied in Chapter 3.

ZEBRA Battery History

The ZEBRA battery was initially developed for electric vehicle applications. It has its name from the "Zeolite Battery Research Africa Project" team at the Council for Scientific and Industrial Research located in South Africa. The first patent was granted in 1978. The development continued in the United Kingdom at AERE Harwell and later at BETA Research and Development (R&D) , which was bought by Anglo American (a British multinational mining company) afterward. Anglo American and AEG (later Daimler) united efforts to continue the development in 1988. The merged company, AEG Anglo Batteries, began the pilot construction of ZEBRA batteries in 1994 but the project was terminated when Daimler merged with Chrysler in 1998. However, MES-DEA, which was formed in 1999 in Switzerland, continued the development (Dustmann, 2004; Sakaebe, 2014). In 2010, FIAMM, a prominent Italian battery manufacturer, and Switzerland-based MES-DEA created a new company, FZSONICK, which manufactures and markets ZEBRA batteries.

In September 2007, BETA R&D was acquired by General Electric (GE) Transportation Division and assisted in the development of sodium batteries for telecommunications, Uninterruptible Power Supply (UPS), hybrid locomotive, and utility applications. In 2010, GE started commercializing a ZEBRA battery. However, in 2015, the latter abandoned the project as a result of a global reorganization. In 2017, the Chilwee Group, a Chinese battery maker, and GE created a new company to provide ZEBRA batteries for industrial and energy storage applications (BatteryIndustry.tech, n.d.; BatteriesInternational, 2015).

System Problem Statement for ZEBRA batteries

The System Problem Statement for ZEBRA batteries using the To-By-Using Framework can be seen in an OPD in Figure 1-17 and its corresponding OPL in Figure B-2. This representation was performed using OPCloud Version 2 .1 (*OPCloud*, n.d.).

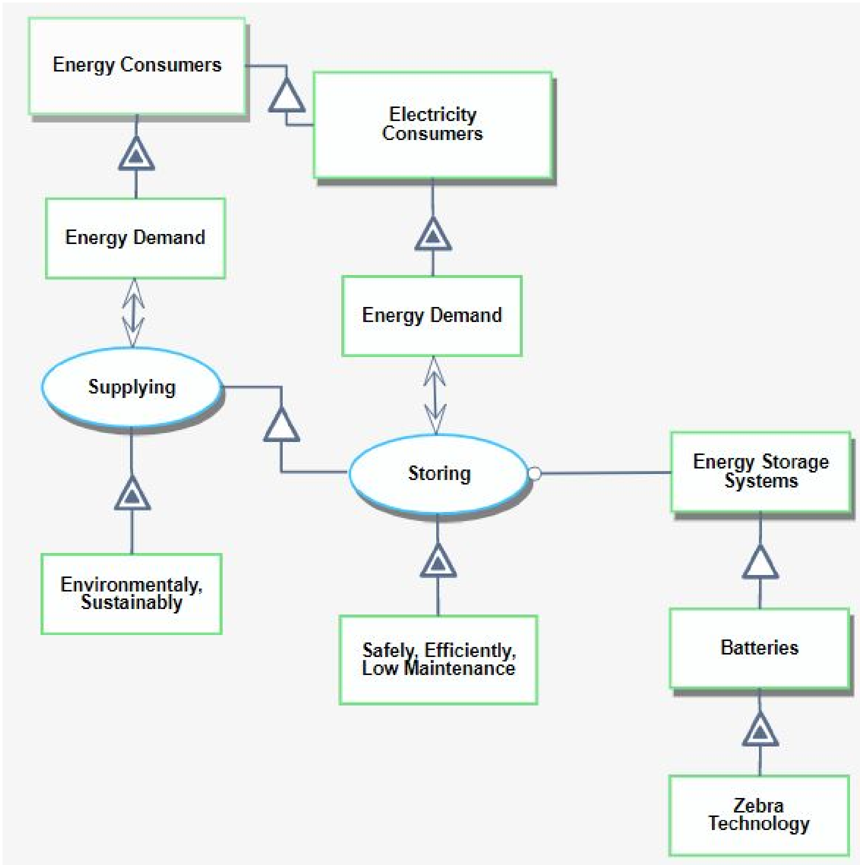


Figure 1-17: SPS for ZEBRA batteries using the To-By-Using framework OPD.

- **TO** environmentally and sustainably supply the energy demand of energy consumers...
- **BY** storing energy for electricity consumers safely, efficiently, and in a low-maintenance way...
- **USING** batteries with ZEBRA technology.

Chapter 2

Technology Roadmap

As Professor Olivier de Weck states: "A technology roadmap is a plan that shows which technologies will be used by which current or future product (or service) and by when these technologies have to be ready and at what level of performance" (*"16.887 Technology Roadmapping and Development"*, 2020).

In this chapter, the framework from the course "16.887 Technology Roadmapping and Development" will be applied to ZEBRA Battery Technology.

2.1 Roadmap Overview

ZEBRA batteries, also known as Sodium Nickel-Chloride batteries, are built by grouping ZEBRA cells that are in arrangements of combined parallel and series connections. Figure 2-1 depicts the schematic of a ZEBRA cell.

When charged, the cathode is made of $NiCl_2$ and the anode of Na metal. The cells are built in the discharged mode with NaCl and Ni metal. Iron (Fe) is added to the cathode to increase the power density and robustness and reduce the cost of the battery. The reactions in the cathode can be seen in Equation 2.1 and Equation 2.2. The discharge reaction in the anode can be seen in Equation 2.3. The overall discharge reactions can be seen in Equation 2.4 and Equation 2.5.

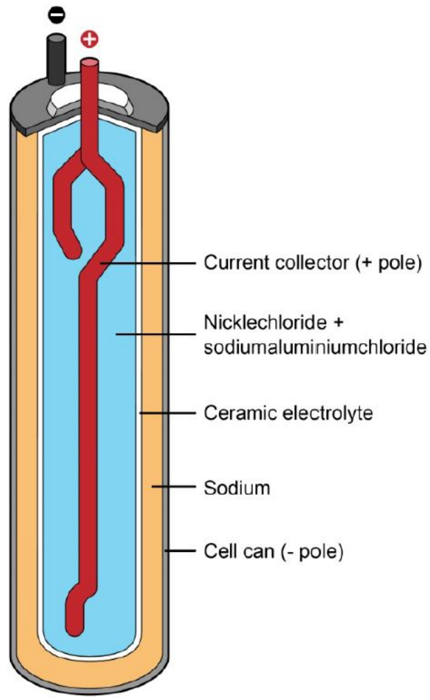


Figure 2-1: ZEBRA Battery cell.

$$NiCl_2 + 2\,Na^+ + 2\,e^- \xrightleftharpoons[\text{Charge}]{\text{Discharge}} 2\,NaCl + Ni \tag{2.1}$$

$$FeCl_2 + 2\,Na^+ + 2\,e^- \xrightleftharpoons[\text{Charge}]{\text{Discharge}} 2\,NaCl + Fe \tag{2.2}$$

$$Na \xrightleftharpoons[\text{Charge}]{\text{Discharge}} Na^+ + e^- \tag{2.3}$$

$$NiCl_2 + 2\,Na \xrightleftharpoons[\text{Charge}]{\text{Discharge}} 2\,NaCl + Ni \qquad E = 2.58\,V \tag{2.4}$$

$$FeCl_2 + 2\,Na \xrightleftharpoons[\text{Charge}]{\text{Discharge}} 2\,NaCl + Fe \qquad E = 2.35\,V \tag{2.5}$$

The cathode and anode are separated by a solid tubular separator of β-alumina, a ceramic material that allows the flow of Na^+. The internal operating temperature is between 270 and 350°C. At that temperature, all the elements melt but not the solid electrolyte. The β-alumina tube is incorporated in the cell tube of stainless steel with Ni plating. $NiCl_2$ and $NaAlCl_4$ are inside the β-alumina tube. The cell case is the current collector for the Na anode. Adding aluminum powder to the cathode allows the reaction expressed in Equation 2.6. The $NaAlCl_4$ compound acts as a liquid electrolyte preventing a sudden polarization in the cell at the end of the discharge process, and as a reserve of Na in case of overcharge, as shown in Equation 2.7 . The cathode is connected to a wire with an internal copper core and an external Nickel plating that acts as a current collector.

$$3\,\mathrm{Na} + \mathrm{NaAlCl_4} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} \mathrm{Al} + 4\,\mathrm{NaCl} \qquad \mathrm{E} = 1.58\,\mathrm{V} \tag{2.6}$$

$$\mathrm{NiCl_2} + 2\,\mathrm{Na} + 2\,\mathrm{AlCl_3} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2\,\mathrm{NaAlCl_4} + \mathrm{Ni} \qquad \mathrm{E} = 3.05\,\mathrm{V} \tag{2.7}$$

The solid electrolyte is a fragile material, and cracks might appear. If that happens, $NaAlCl_4$ comes in contact with Na forming NaCl and Al metal (Equation 2.8), filling the gap if it is small. If the crack is not small, Al causes a short-circuit between the positive and negative electrodes. In that case, the cell loses voltage, but the battery (system of cells) can operate while the failed cells are less than 5–10% of the total cells (Sakaebe, 2014; Sudworth, 2001).

$$3\,\mathrm{Na} + \mathrm{NaAlCl_4} \longrightarrow \mathrm{Al} + 4\,\mathrm{NaCl} \tag{2.8}$$

These batteries are built as modular units that can be scaled to store energy from kWhs to tens of MWhs. The arrangement of a module with multiple cells can be seen in Figure 2-2. The arrangement of a group of modules can be seen in Figure 2-3.

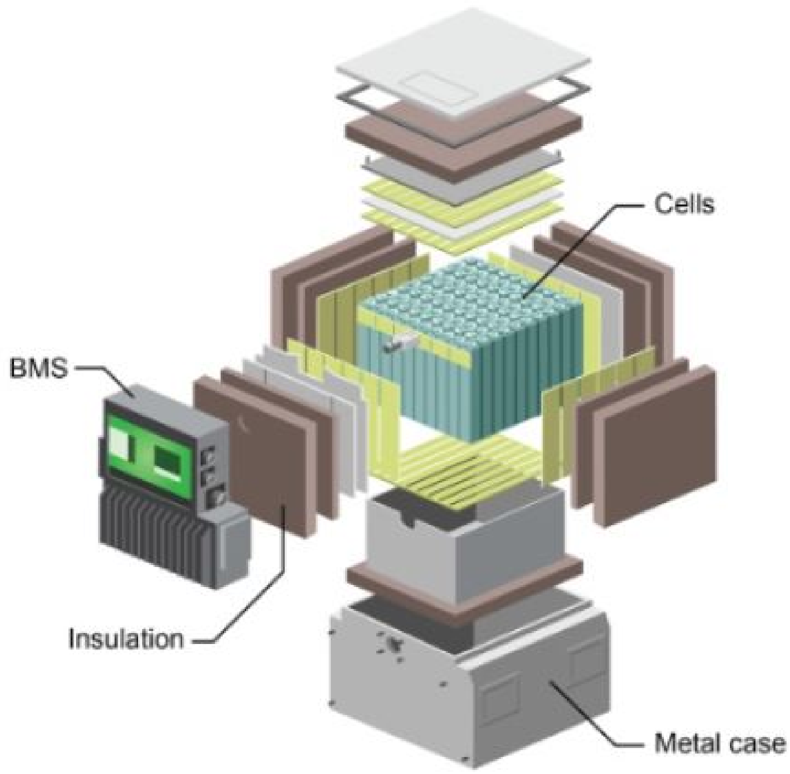


Figure 2-2: ZEBRA module with multiple cells.

Figure 2-3: Multiple ZEBRA modules arrangement.

2.2 Design Structure Matrix (DSM) Allocation

The ZEBRA battery technology roadmap (1ZB) shown in Figure 2-5 can be extracted from the DSM in Figure 2-4. In these figures, it is possible to recognize roadmaps that are linked to 1ZB roadmap at different levels. These linking relationships can be based on R&T projects that require progress in another technology or others that compete among them until one of them is clearly the winner (*"16.887 Technology Roadmapping and Development"*, 2020).

1ZB requires key enabling technologies at the subsystem level: 2MTR (Materials), 2MNF (Manufacturing), and 2CONT (Controllers and Interfaces). These level 2 technology roadmaps require enabling technologies at level 3. 2MTR requires 3CATH (materials for cathodes), 3 SEPA (materials for separators), 3 INSU (materials for insulators) and 3 AMIN (alternative methods to extract minerals). 2MNF requires 3 SMDF (sustainable manufacturing) and 3 DSCH (distributed supply chain). Finally, 2CONT requires 3AIOT (Applied Internet of things), 3AAI (Applied Artificial Intelligence), and 3SMGI (Smart Grid Interfaces).

	1 ZB	2 MTR	2 MNF	2 CONT	3 CATH	3 SEPA	3 INSU	3 AMIN	3 SMNF	3 DSCH	3 AIOT	3 AAI	3 SMGI
1 ZB		X	X										
2 MTR	X			X	X	X	X						
2 MNF	X							X	X	X			
2 CONT		X									X	X	X
3 CATH		X											
3 SEPA		X											
3 INSU		X											
3 AMIN			X										
3 SMNF			X										
3 DSCH			X										
3 AIOT				X									
3 AAI				X									
3 SMGI				X									

Figure 2-4: 1ZB Technology Roadmap - DSM

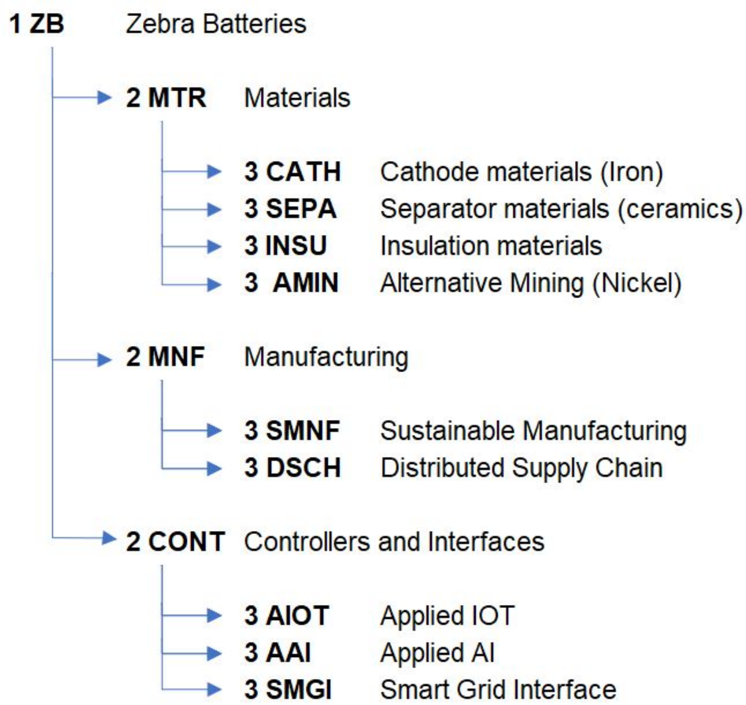


Figure 2-5: 1-ZB Technology Roadmap - Tree

2.3 Roadmap Model

An OPD of the 1ZB roadmap is displayed in Figure 2-6. This diagram captures the main object of the roadmap, its instances, its decomposition into subsystems (cells, insulation, case, and Battery Management System (BMS)), its characterization by Figures of Merit (FOMs), and the main process that is Storing. The corresponding OPL, shown in Figure B-3, reflects the same content in a formal natural language so as to avoid misunderstandings regarding 1ZB roadmap scope.

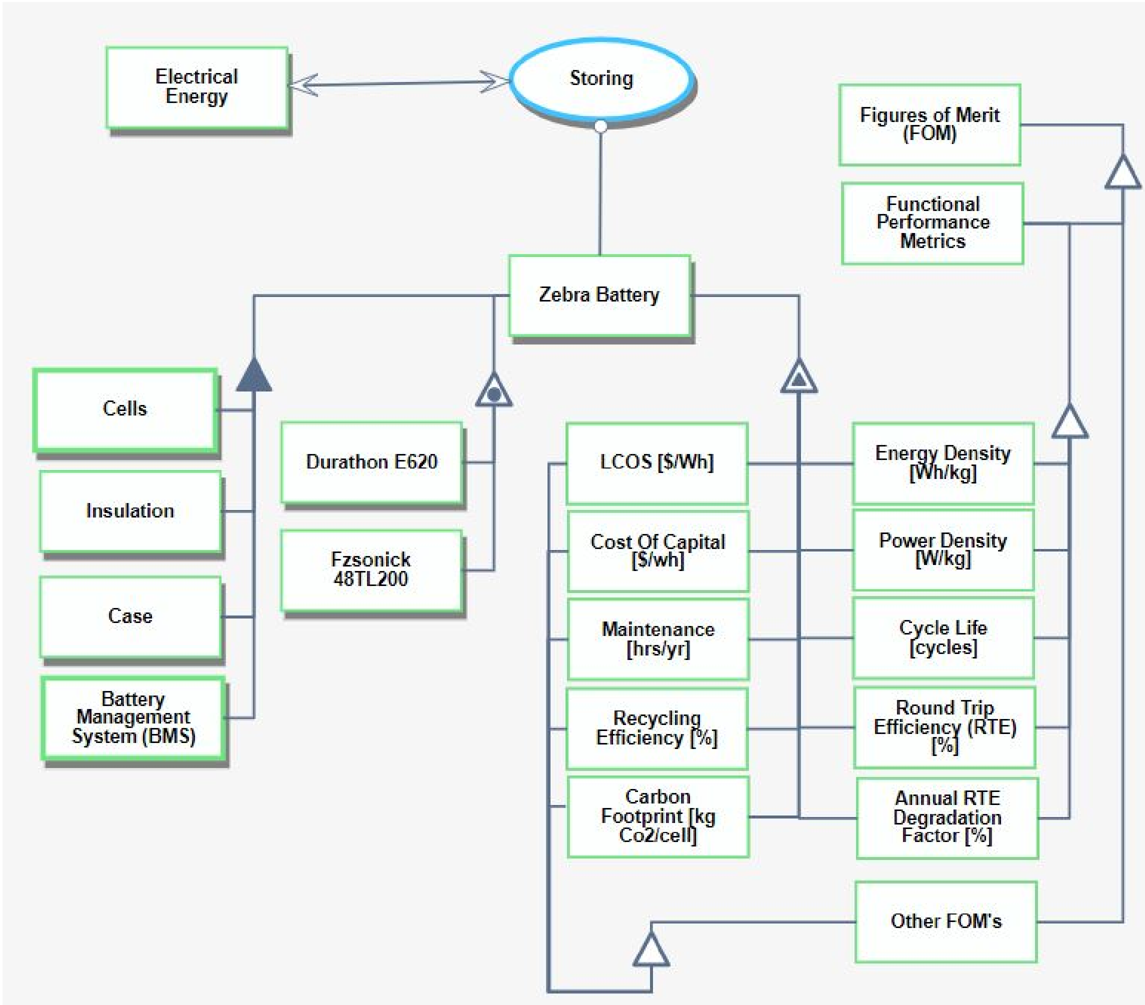


Figure 2-6: System-level diagram (SD) for ZEBRA Battery OPD.

An OPD that zooms in the Storing process can be observed in Figure 2-7 and its corresponding OPL in Figure B-4.

An OPD that zooms in the ZEBRA battery cells components can be seen in Figure 2-8 and its corresponding OPL in Figure B-5.

An OPD that zooms in the Battery Management System components according to Miao et al. (2019), can be seen in Figure 2-9 and its corresponding OPL in Figure B-6.

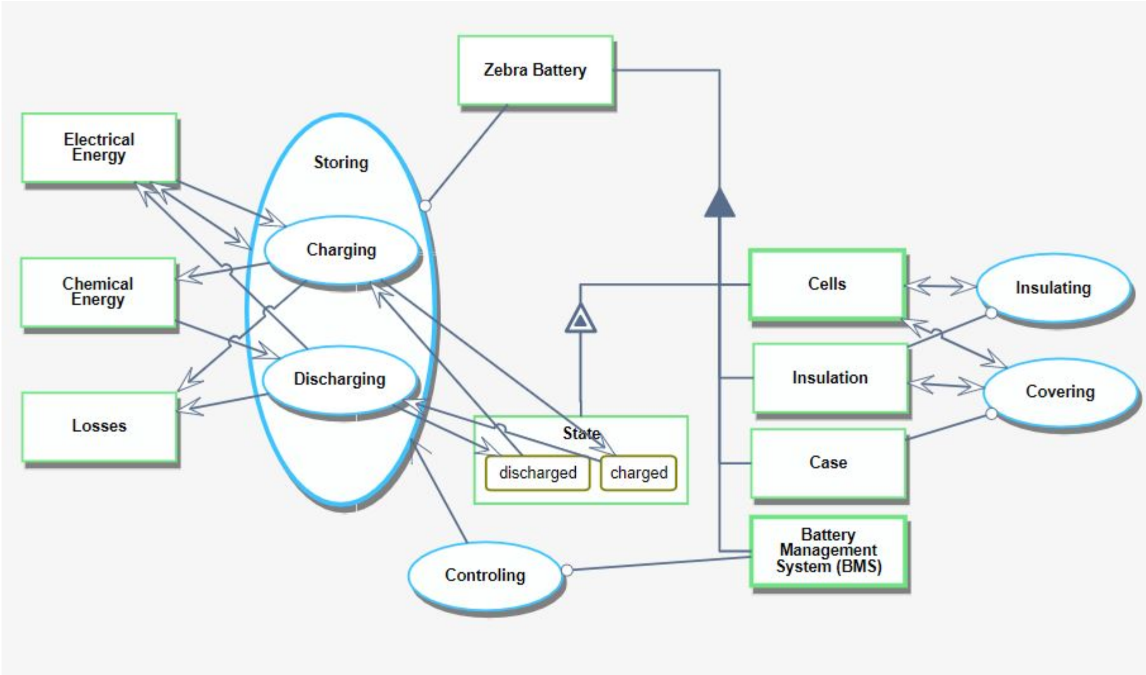


Figure 2-7: Subsystem level diagram (SD1.1) for Storing OPD.

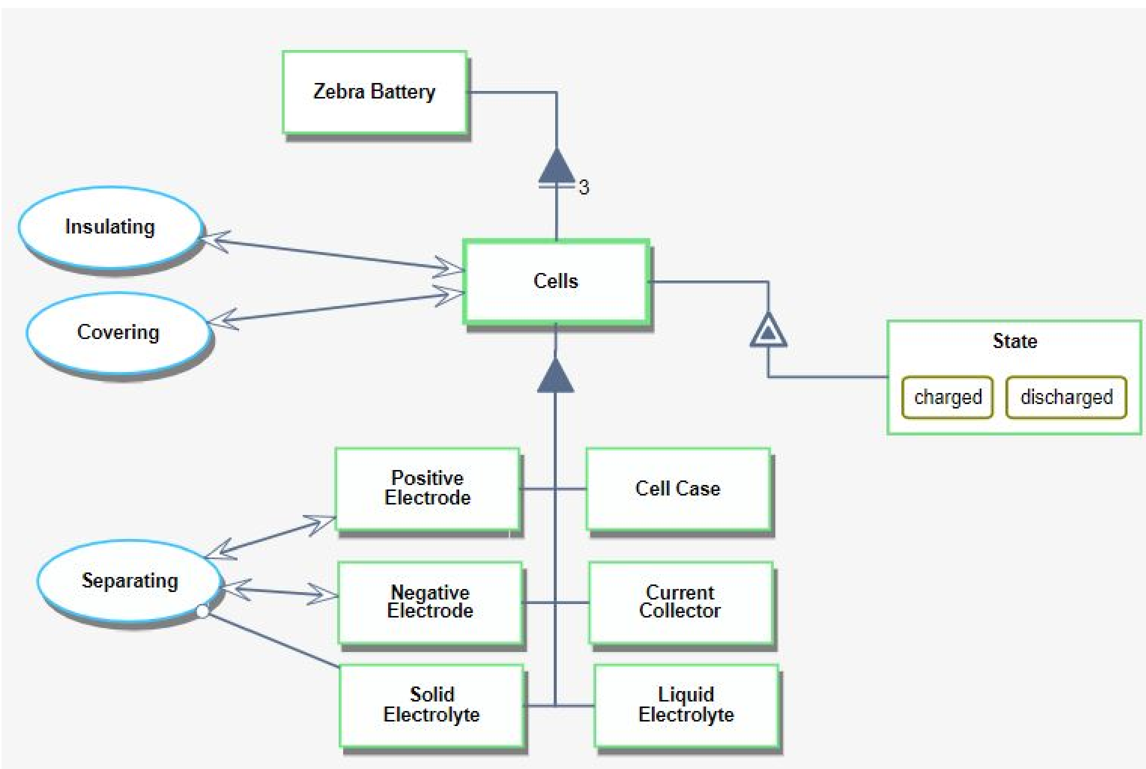


Figure 2-8: Subsystem level diagram (SD1.2) for ZEBRA Battery Cells OPD.

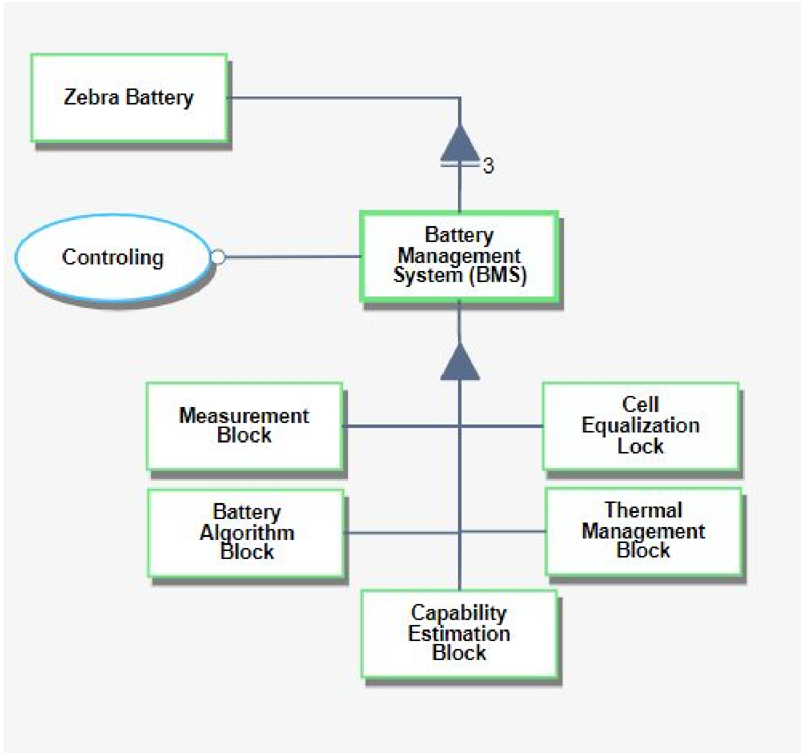


Figure 2-9: Subsystem level diagram (SD1.3) for Battery Management System OPD.

2.4 Figures of Merit (FOMs): Definition, name, unit, trends dFOM/dt

A FOM is a scalar quantity that enables quantifying the progress of technology over time. It can be non-dimensional or have specific units of measurement. Any technology roadmap must define the FOMs that will be used to identify the current status of the technology, its historical trends, and its future evolution (*"16.887 Technology Roadmapping and Development"*, 2020).

FOMs are used to track ZEBRA Technology's advancement over time and compare it to other energy storage systems. Some of them were shown before in Figure 2-6.

2.4.1 Traditional FOMs for batteries

Table 2.1 shows a list of the FOMs by which ZEBRA batteries and batteries in general can be assessed. Most of them are Functional Performance Metrics (FPMs), i.e., they measure how well a technology performs its function.

FOM	Units	Description
Capital Cost	$/kWh	Capital cost expresses the cost per unit of stored energy.
Levelized Cost of Storage (LCOS)	$/kWh	The cost to design, construct, and utilize the ESS over its economic life cycle.
Energy Density	Wh/kg	Energy density expresses how much energy can be stored per kg.
Power Density	W/kg	Power density expresses how quickly energy can be delivered per kg.
Cycle Life	cycles	The cycle life of a cell is the number of cycles it can perform until its capacity reaches 80% of its initial value.
Round-Trip Efficiency (RTE)	%	It is the ratio of net energy that is discharged to the grid to the total energy used to charge the battery.
Annual RTE Degradation Factor	%	It is the degradation of the RTE (positive percentage number) from one year in comparison to the previous one.

Table 2.1: FOMs for batteries. Source: Mongird et al. (2019); fzsonick (n.d.).

Other parameters that are useful to characterize different batteries but may not be considered as FOMs are:

- Voltage: The voltage of a galvanic cell is determined by the electrochemical characteristics of the chemicals used in it.
- Maximum Depth of Discharge (DOD): It indicates the maximum value for the percentage of the battery that is discharged compared to its total capacity.
- Maximum C-rate: It indicates the maximum velocity for a battery to be discharged. The discharge current is expressed as a C-rate, which measures the

discharge current relative to the battery capacity. A 1C rate indicates that the battery will be discharged in 1 hour at that specific discharge current (*MIT Electric Vehicle Team*, 2008).

Degradation Rate

The degradation rates of batteries depend on several variables such as Environment Operating Temperature, DOD and Discharge current (C-rate) (Preger et al., 2020). Even for the same battery technology, the different use cases will determine a different profile of charge/discharge as shown in Table 2.2.

Use case	Energy capacity	Life Cycle	C-rate
Electronics	0.5-50 Wh	> 1000 cycles For phones or laptops: 1 cycle/day for 2-3 years	Charge: 20 minutes Discharge: 24 hours/days
EV	29-200 kWh	333 cycles under warranty (warranty: 100,000 miles) 1 cycle/300 miles	Charge: 2-6 hours Discharge: 1 week (assuming 50 miles/day)
Electric Grid	0.1-500 MWh	> 3500 cycles (coupled with VRE) 1 cycle/day for 10-years ESS	Charge: 2-12 hours Discharge: 2-12 hours

Table 2.2: Use cases for Batteries. Source: Chiang & Chueh (n.d.); Voelcker (2021).

As this study is focused on ESS applications, it is of main interest to study the performance of batteries under "peak-shaving duty cycles." Studies about the degradation process under these conditions are very recent and scarce. Some results for ZEBRA batteries can be studied in the article Shamim et al. (2021) while the article Preger et al. (2020) shares results for LIBs. In general terms, ZEBRA batteries have a slower degradation rate than the LIBs. This will be analyzed in section 3.3.

Regarding the performance of LIB technology for ESS applications, Professor

Donald Sadoway from MIT states: "There's a temptation to take lithium-ion, which we know a lot about, it's served us very well in phones and computers, and try to scale up... we don't have any evidence of lithium-ion batteries lasting ten plus years. Nobody has a 10-year-old phone in his pocket." (Sadower & Shao-Horn, n.d.).

2.4.2 New FOMs for batteries

Technology can be classified as sustaining or disruptive. Sustaining technologies improve existing products for well-established FOMs that often drive the competition. In contrast, disruptive technologies often exhibit a lower performance on incumbent FOMs but offer a new value proposition on a different FOM (or set of FOMs) to a different group of customers (*"16.887 Technology Roadmapping and Development"*, 2020; Christensen, 1997). Table 2.3 is a list of new and additional FOMs by which ZEBRA batteries and batteries, in general, can be assessed.

FOM	Units	Description
Recyclability	%	Percentage of the battery that can be recycled.
Flammability	FI	Flammability Index by component
Health Toxicity	PPM	Released components that may affect the health of the users
Environmental Toxicity	PPM	Released components that may pollute the environment
Safety records	incidents/ yr-100 k batteries	normalized number of incidents per year
Maintenance	hrs/yr USD/kWh-yr	Hours of maintenance per year Operations and Maintenance (O&M) costs
Carbon footprint	kg CO_2 / cell	Mass of CO_2 per manufactured cell

Table 2.3: New FOMs for batteries.

Another factor that may not be considered as a FOM but is considered necessary is that the batteries must be built and sourced ethically and healthily. Third-party certifications should be in place.

Maintenance

According to the ZEBRA batteries data-sheet, they do not require maintenance throughout their life, as there are no user-serviceable elements inside the module or Battery Management System (BMS) (fzsonick, n.d.). In contrast, LIBs do require maintenance schedules that are being analyzed and optimized (Zhang & Lee, 2011). The study made by Mongird et al. (2019) does not make any difference in O&M Fixed Costs ($/kW-yr) between LIBs and ZEBRA batteries. A cost of 10 $/kW-yr is considered for both technologies.

Safety

In general terms, battery safety is defined by the active material and electrolyte chemistry, heat generation and dissipation speed, and external forces tolerance.

ZEBRA batteries have a very high safety performance in comparison with other battery technologies. They do not require active cooling. Its ambient temperature range of operation is -20°C to +60°C (-4°F to +140°F), but it can operate during temperature peaks in a broader range (-40°C to +75°C / -40°F to +167°F). This battery is free of toxic materials and it does not have the risk of gassing or explosion even in the presence of external fire. The battery has an embedded Direct current (DC) protection for load disconnection and short circuit protection (fzsonick, n.d.).

There are rising concerns regarding LIBs' safety. For this technology, it is impossible to remove the heat generated by the battery entirely, particularly on hot days or in a big battery pack. High battery temperature and high voltage would initiate electrolyte/electrode parasitic reactions, causing thermal runaway, resulting in battery rupture and subsequent explosion due to the reaction of the battery's hot ignitable gases with oxygen in the ambient environment. To prevent high-temperature conditions, a cooling system is needed (Chen et al., 2021). The cooling system would be considered in the economics of any ESS project with this technology, as it can impact O&M costs.

Carbon Footprint

FZSONICK, one of the biggest manufacturers of ZEBRA batteries, tracks the carbon footprint of its production and shares this information on its website which can be seen in Figure 2-10.

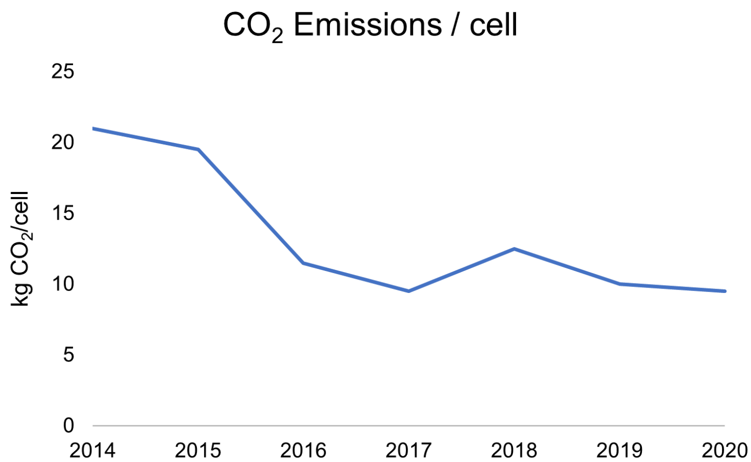


Figure 2-10: FZSONICK CO_2 emissions by cell. Source: fzsonick (n.d.).

Recyclability

According to Galloway & Dustmann (2003), ZEBRA batteries have had a recycling process implemented for the last two decades. The American company Inmetco recycled 20 tonnes of ZEBRA cells by adding them to their submerged-arc furnace to produce a Nickel-rich material and sourced the stainless steel industry. Additionally, the β-alumina and $NaCl_2$ contained in the cells were collected and sold to replace limestone in road construction. ZEBRA battery customers in Europe were required to return worn ZEBRA batteries to MESDEA. After extraction of the BMS, they were packaged in their case and shipped to Inmetco. Although the shipping cost was high, the nickel's worth covered the transportation cost, resulting in a cost-neutral recycling process. The recycling process of ZEBRA batteries is shown in an OPD in Figure 2-11 and Figure 2-12 and its corresponding OPL can be seen in Figure B-7 and Figure B-8.

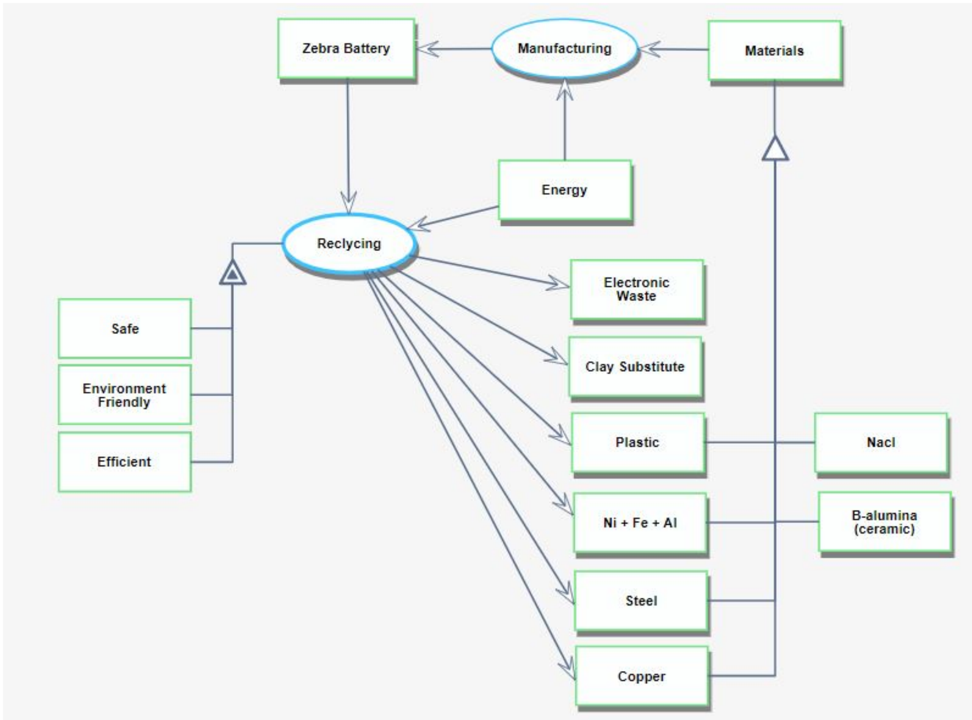


Figure 2-11: System-level diagram (SD) for ZEBRA Batteries Recycling and Manufacturing Processes OPD.

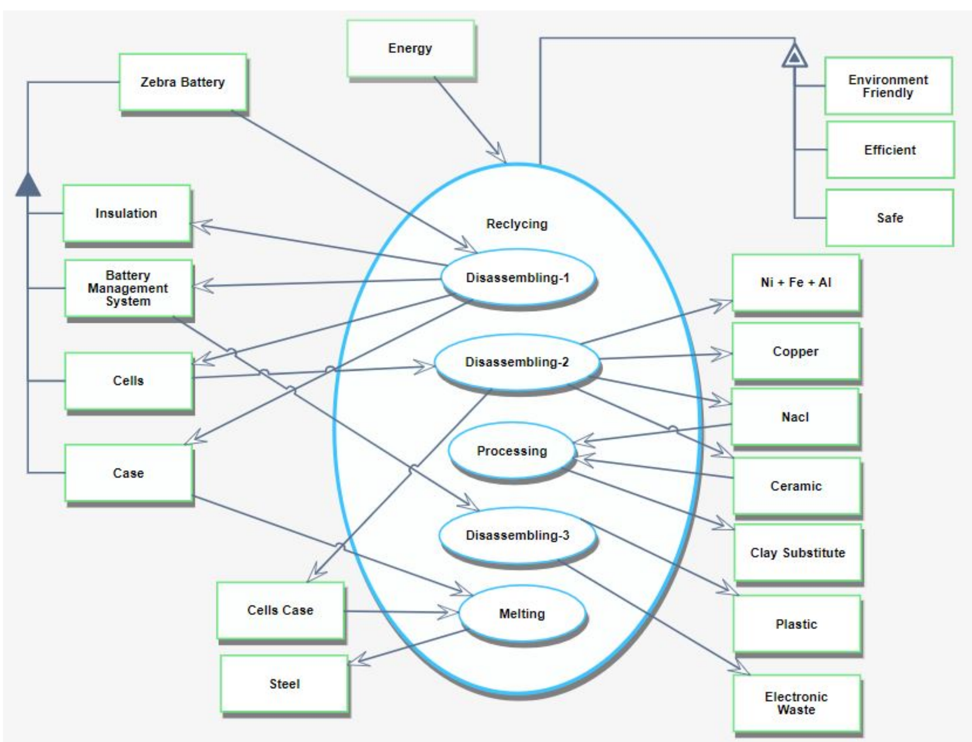


Figure 2-12: Subsystem level diagram (SD1) for Recycling OPD.

European Union (EU) - Background

Understanding the EU background is important as ZEBRA Batteries are currently mostly developed by FZSONICK, which has its assembly plant in Stabio, Switzerland, and whose production capability is over 1M cells/yr (fzsonick, n.d.).

The EU is developing a new regulatory framework for batteries (Halleux, 2021). This proposal aims to promote a circular economy, reducing environmental and social impacts throughout the whole battery life-cycle. This proposal includes new requirements for rechargeable industrial batteries like ZEBRA batteries:

- **Carbon footprint:** Increasing requirements to minimize it.
- **Minimum levels of recycled content:** 4% nickel by 2030 and 12% by 2035.
- **Safety requirements** for stationary battery ESS.
- **Nickel recovery targets** 90% by the end of 2025 and 95% by 2030.
- **Battery management system:** labeling and information requirements, "creation of a battery passport," etc.

2.5 Alignment with Company Strategic Drivers: FOM targets

This section shows the link between the company's strategy and the product's targets that should be achieved, expressed in FOMs (*"16.887 Technology Roadmapping and Development"*, 2020).

Number	Strategic Driver	Alignment and Target
1	To increase ZEBRA battery market share in ESS projects.	To increase sales by 100% in 5 years.
2	To reduce the cost of the battery.	Value target: 480 USD/kWh by 2025 (15% cost reduction of the current price) and 360 USD/kWh (40% cost reduction of the current price) by 2035.

Table 2.4: Company Strategic Drivers and Targets.

Target #1 was determined based on the information shown in section 1.2 about the market share of ZEBRA battery technology in ESS, which is relatively low in comparison to LIBs.

Target #2 was set according to Schmidt et al. (2017). It explains that an average value of capital costs of 340 USD/kWh for installed stationary systems and 175 USD/kWh for battery packs can be achieved once 1 TWh of cumulative capacity is installed for each battery technology studied in the article.

2.6 Positioning of Company vs. Competition: FOM charts

This section aims to perform a quantitative benchmarking of the company's situation compared to the present and possible future of its competition through FOMs charts. (*"16.887 Technology Roadmapping and Development"*, 2020).

As mentioned in Chapter 1, this thesis is focused on the applications related to electrical energy storage that would enable renewable energy to increase its participation in the electric market. For that reason, Figure 2-13 shows the performance of ZEBRA battery technology (Product Price vs. Cumulative Capacity) and its cost targets among other ESS technologies. In Figure 2-14 it is possible to see a Tradespace (Power Density vs. Energy Density) for batteries technologies.

The performance of the ZEBRA battery in Figure 2-13 responds to:

- **Product price:** Range: 520 - 1000 USD/kWh (2017), average 700 USD/kWh, obtained from Mongird et al. (2019). FZSONICK batteries cost around 600 USD/kWh, according to the company.
- **Cumulative installed capacity:** FZSONICK has manufactured and produced ZEBRA Batteries that accumulate more than 1 GWh installed capacity (fzsonick, n.d.).

The targets from section 2.5 are indicated in red in Figure 2-13.

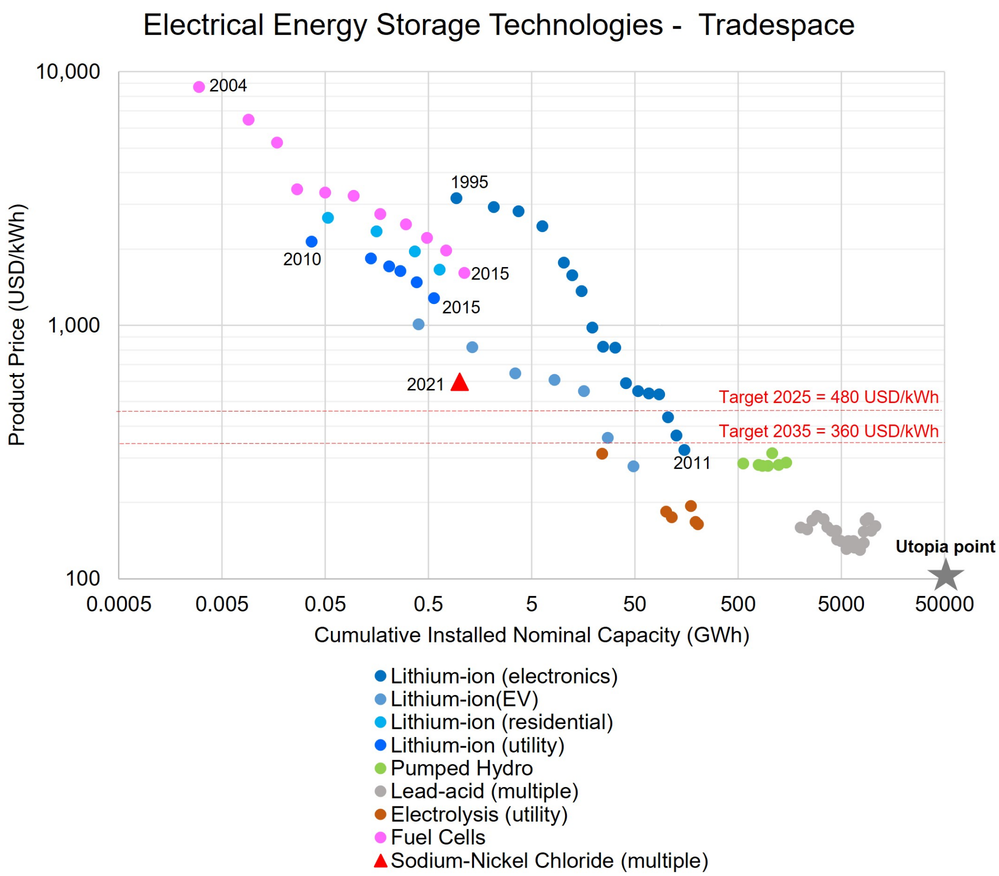


Figure 2-13: ESS Tradespace. Adapted from Schmidt et al. (2017).

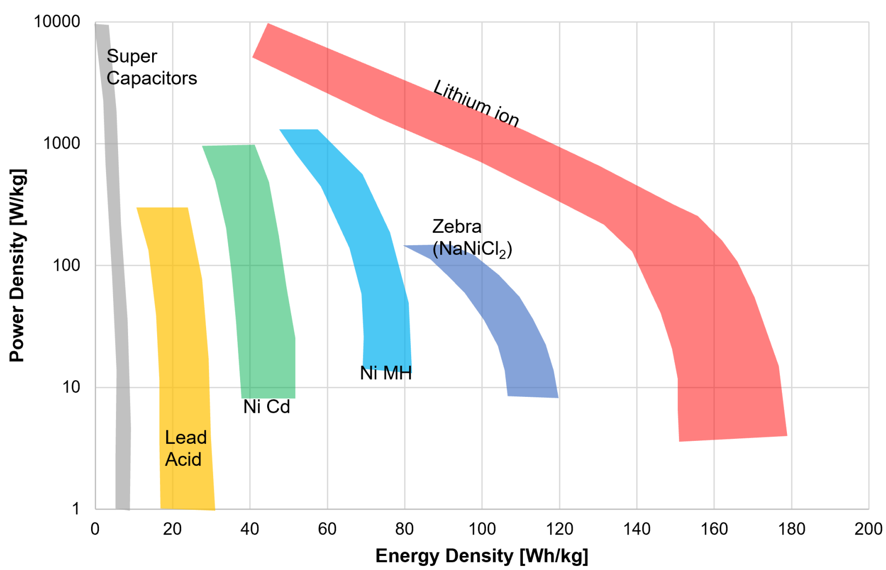


Figure 2-14: Batteries Tradespace. Adapted from *Road Transport: The Cost of Renewable Solutions* (2013).

2.6.1 Comparison

A comparison of four different kinds of batteries is shown in Table 2.5.

Technology	NMC	ZEBRA	Valve Regulated Lead Acid (VRLA)	LFP
Manufacturer	TESLA	FZSONICK	GNB Sonnenschein PBA	Simpliphi
Battery Name	Powerwall 1	48TL200	Sonnenschein SB 6/330	PHI 3.4
Rated Capacity [kWh]	6.4	9.6	1.8	3.44
Energy Density [Wh/kg]	66	92	37.5	98.8
Voltage [V]	350-450	48	6	51.2
Life [cycles]	> 5000 (warranty)	> 4500 at 80% DoD	1200 at 60% DoD	> 10000
Environment Operating Temperature Range	-20°C / + 50°C	-20°C / + 60°C	15°C / 35°C	-20°C / + 60°C
Capital Cost [USD/kWh]	500	600	280	800

Table 2.5: Comparison between different types of batteries. Source: gridedge (n.d.); *Lithium Ion Battery Test Centre* (n.d.); fzsonick (n.d.); Mongird et al. (2019)

2.6.2 Lead-acid Batteries

Lead-acid battery technology was invented more than one hundred years ago. It is the most utilized rechargeable battery in applications such as automobiles, UPS, and telecommunications. Although this type of battery has some advantages like high RTE and low cost, its disadvantages outweigh its benefits. Lead-acid batteries have a low energy density and short cycle life, and they are toxic because of the use of sulfuric acid, which may raise environmental concerns. These disadvantages limit the use of this technology for energy storage applications (Ding et al., 2015). Actually, according to McKenna et al. (2013), these batteries are not appropriate for domestic-scale hybrid systems like photovoltaics and energy storage.

2.6.3 LIBs

Table 2.6 draws a comparison between ZEBRA and LIBs based on the information provided in the previous sections of this chapter.

Variables	ZEBRA battery	LIB
Capital Cost [USD/kWh]	500-1000	350-800
Energy Density [Wh/kg]	80-120	40-180
Energy Power [W/kg]	10-180	10-10,000
Market penetration	Mainly telecommunications applications	State-of-the-art technology applied to electronics and EVs
Safety	No risk of explosion or fire.	Risks related to high-temperature or high-voltage conditions.
Temperature of operation	+60°C maximum range for normal operation with peaks of 75°C. No cooling needed.	+50°C at maximum of normal operations, High temperature accelerates its degradation rate, cooling needed
Maintenance	Maintenance free	Require scheduled maintenance
Recyclability	100% recyclable in a safe and simple process	Recycling process is more complicated than for ZEBRA Batteries
Earth-abundant materials	Nickel and table salt	Nickel, Cobalt and Lithium
Fair labor conditions along the supply chain	-	Cobalt supply is related to child labor.
Environmental impact along the supply chain	-	There is evidence that current methodology used by the Lithium mining companies has a negative impact on the environment.
Degradation rate	Lower degradation rate than LIBs. Not related to Temperature.	Influenced by Temperature

Table 2.6: Comparison between ZEBRA batteries and LIBs.

2.7 Technical Model: Morphological Matrix and Tradespace

The purpose of this section is to investigate the design tradespace and identify the constraints in the system. The morphological matrix shows the main selection alternatives for the technology at the first level of decomposition (*"16.887 Technology Roadmapping and Development"*, 2020; Christensen, 1997). The morphological matrix for ZEBRA battery technology shown in Table 2.7 illustrates the current materials and methods for various critical design decisions. The proposed R&T projects of this roadmap could include these options and additional ones for exploration.

Parameter	Option #1	Option #2	Option #3
Size	Individual: 3.65 kWh - 22.5 kWh	Modular	
Anode	Na		
Cathode	$NiCl_2$	$FeCl_2$	Mix
Solid Electrolyte	β-alumina	Nasicon	
Liquid Electrolyte	$NaAlCl_4$		
Case	Steel		
BMS	Individual	Modular	
Shape of cell	Tubular	Planar	
Shape of the Solid Electrolyte	Cylindrical tube	Cloverleaf design	

Table 2.7: Morphological Matrix for ZEBRA battery technology

2.8 Financial Model : Technology Value (NPV)

In this section, a financial model is built to quantify the impact of a particular new technology on a business plan that only includes well-established technologies.

The NPV calculation is done taking into account incremental sales caused by the improvements in the technology. The analysis is done for the period 2022 to 2050. A budget for each project in section 2.9 is assumed. The total cost is 15 MUSD and its breakdown is shown in Figure 2-15. An incremental sales of 10 MWh is assumed in 2023, and it continues growing annually by 20% until 2035, when it remains constant.

Project	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	Total
Lower cost B-Alumina ceramic [k USD]	750	750	750	750	-	-	-	-	-	-	-	-	-	3,000
Lower cost of cells by partially replacing nickel with iron [k USD]	625	625	625	625	625	625	625	625	-	-	-	-	-	5,000
Better and cheaper insulation materials [k USD]	750	750	750	750	-	-	-	-	-	-	-	-	-	3,000
Alternative mining process to ensure Nickel supply [k USD]	77	77	77	77	77	77	77	77	77	77	77	77	77	1,000
Efficient recycling process to recover Nickel [k USD]	250	250	250	250	250	250	250	250	250	250	-	-	-	2,500
BMS - Electrical Model for Zebra Batteries	125	125	125	125	-	-	-	-	-	-	-	-	-	500
Total [k USD]	2,577	2,577	2,577	2,577	952	952	952	952	327	327	77	77	77	**15,000**

Figure 2-15: R&T Projects Cost for ZEBRA battery improvements - Timeline

The battery sale price in 2022 is 600 USD/kWh. An annual sale price reduction of 7% is assumed for 2023, 2024, and 2025 to achieve the target of 480 USD/kWh by 2025. After that, an annual sale price reduction of 3% is assumed up to 2035 to achieve the target of 360 USD/kWh. No more improvements in the sale price or investments are considered after 2035. It is considered that the cost of production is 70% of the sales price. Finally, the NPV is calculated considering 12% of taxes and 10% of the Internal Rate of Return (IRR). The NPV is equal to 30 MUSD, and the incremental sales represent a total of 1.8 GWh of capacity. The discounted cash flow and the cumulative discounted cash flow can be seen in Figure 2-16 and Figure 2-17. In the year 2030, the cumulative discounted cash flow becomes positive ("break-even"), that is to say, the investment is recovered by then.

A probabilistic analysis of the NPV and the incremental Sales capacity is performed by assigning triangular probability functions to three variables. The CAPEX has a minimum value of 10 MUSD, a mode of 15 MUSD, and a maximum value of 20 MUSD. The incremental sales value in 2023 has a minimum value of 5 MWh, a mode of 10 MWh, and a maximum value of 20 MWh. The sales growth rate has a minimum value of 5%, a mode of 20%, and a maximum value of 40%. The outputs of the analysis are shown in Figure 2-18 and Figure 2-19.

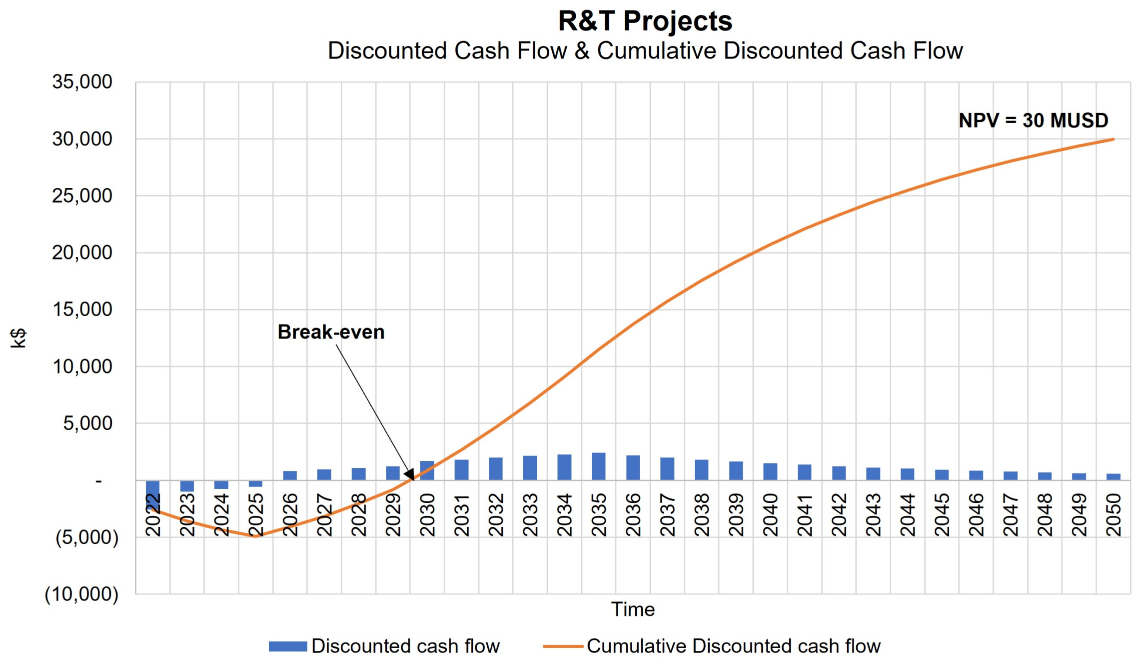


Figure 2-16: R&T Projects discounted cash flow and cumulative discounted cash flow.

Year	Year	Incremental sales	Price	Production Cost	Revenue	CAPEX	Tax	Cash flow	Discounted cash flow	Cumulative discounted cash flow
		kWh	USD/kWh	USD/kWh	k USD	k USD	k USD	k USD	k USD	k USD
2022	0		600			2,577		(2,577)	(2,577)	(2,577)
2023	1	10,000	558	391	1,674	2,577	201	(1,104)	(1,003)	(3,580)
2024	2	12,000	519	363	1,868	2,577	224	(933)	(771)	(4,351)
2025	3	14,400	483	338	2,085	2,577	250	(742)	(558)	(4,909)
2026	4	17,280	468	328	2,427	952	291	1,184	808	(4,101)
2027	5	20,736	454	318	2,825	952	339	1,534	952	(3,148)
2028	6	24,883	440	308	3,288	952	395	1,942	1,096	(2,052)
2029	7	29,860	427	299	3,827	952	459	2,416	1,240	(812)
2030	8	35,832	414	290	4,455	327	535	3,593	1,676	864
2031	9	42,998	402	281	5,186	327	622	4,236	1,797	2,661
2032	10	51,598	390	273	6,036	77	724	5,235	2,018	4,679
2033	11	61,917	378	265	7,026	77	843	6,106	2,140	6,819
2034	12	74,301	367	257	8,178	77	981	7,120	2,269	9,088
2035	13	89,161	356	249	9,519		1,142	8,377	2,427	11,514
2036	14	89,161	356	249	9,519		1,142	8,377	2,206	13,720
2037	15	89,161	356	249	9,519		1,142	8,377	2,005	15,726
2038	16	89,161	356	249	9,519		1,142	8,377	1,823	17,549
2039	17	89,161	356	249	9,519		1,142	8,377	1,657	19,206
2040	18	89,161	356	249	9,519		1,142	8,377	1,507	20,713
2041	19	89,161	356	249	9,519		1,142	8,377	1,370	22,083
2042	20	89,161	356	249	9,519		1,142	8,377	1,245	23,328
2043	21	89,161	356	249	9,519		1,142	8,377	1,132	24,460
2044	22	89,161	356	249	9,519		1,142	8,377	1,029	25,489
2045	23	89,161	356	249	9,519		1,142	8,377	936	26,424
2046	24	89,161	356	249	9,519		1,142	8,377	850	27,275
2047	25	89,161	356	249	9,519		1,142	8,377	773	28,048
2048	26	89,161	356	249	9,519		1,142	8,377	703	28,751
2049	27	89,161	356	249	9,519		1,142	8,377	639	29,390
2050	28	89,161	356	249	9,519		1,142	8,377	581	29,971

Figure 2-17: R&T Projects NPV calculation.

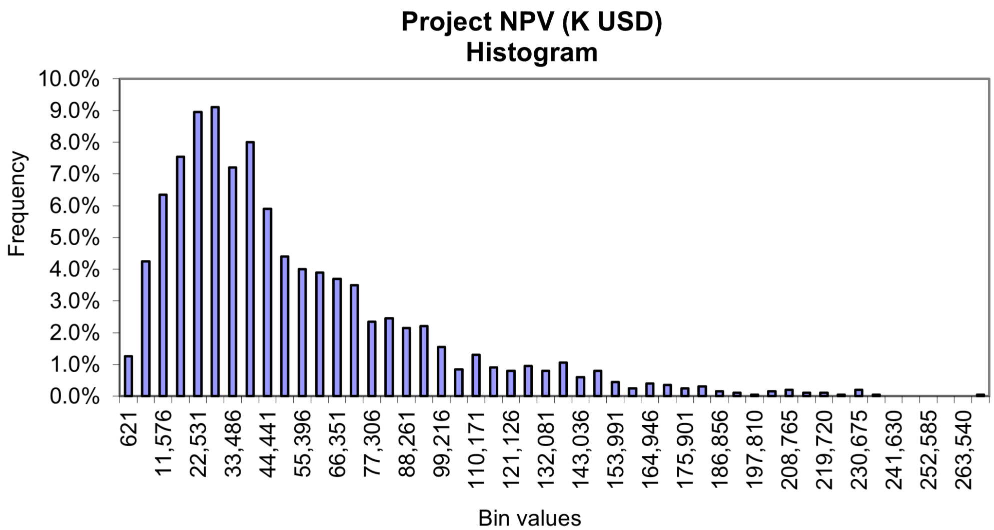


Figure 2-18: R&T Projects NPV Probabilistic analysis.

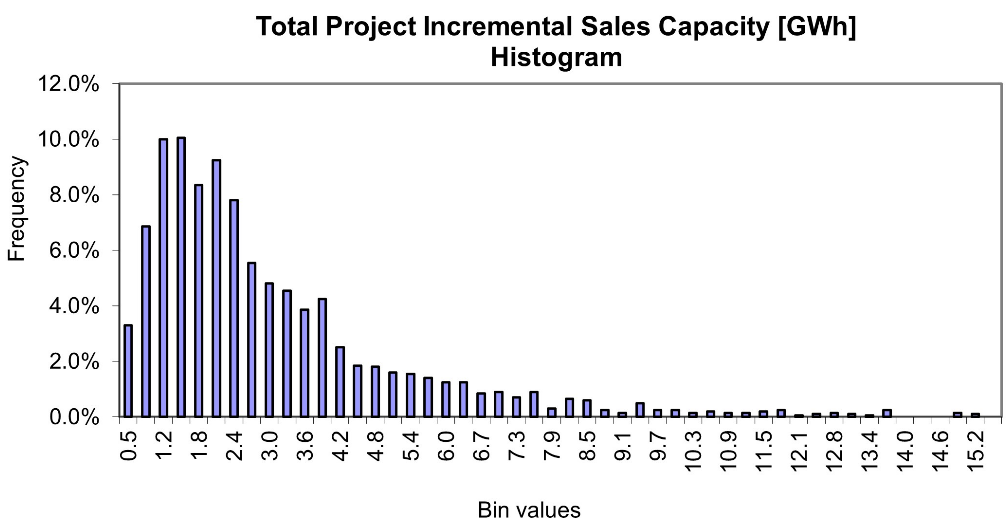
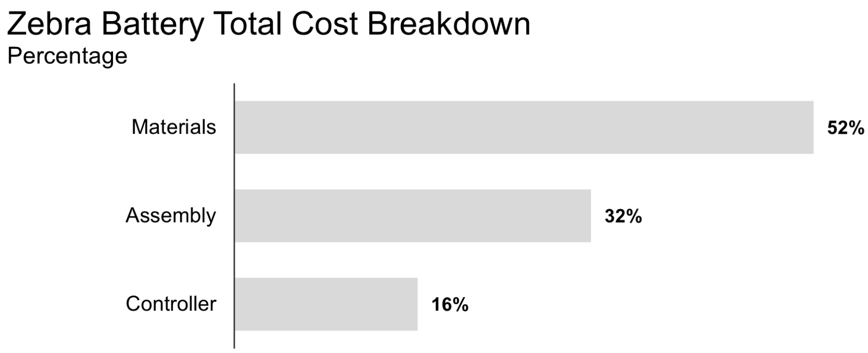


Figure 2-19: R&T Projects Incremental Sales Probabilistic analysis.

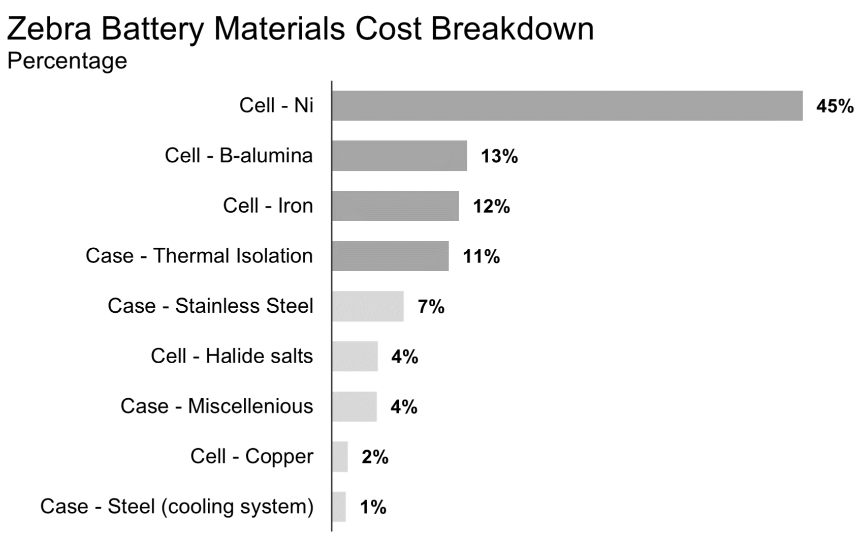
2.9 Portfolio of R&T Projects and Prototypes

The decision about which projects to invest in is guided to achieve the product FOM-based targets expressed in section 2.5. The analysis performed in section 3.3 will show that the most important driver is to reduce the Capital Cost of the battery when competing with LIBs. To understand where to focus on, a cost breakdown for a

21 kWh ZEBRA battery is shown in Figure 2-20 and it is based on a study conducted in 2003 (Galloway & Dustmann, 2003).



(a)



(b)

Figure 2-20: ZEBRA Battery Cost Breakdown. Adapted from Galloway & Dustmann (2003).

The largest cost component of the ZEBRA battery is materials, accounting for 52% of the cost. More than 80% of the materials cost is allocated to Nickel, β-Alumina, and Iron materials in the cell and the thermal insulation material in the case (highlighted in dark grey in Figure 2-20).

The second-most important category that impacts the total cost of the ZEBRA battery is the cost of the battery assembly that represents 32% of the total cost.

The assembly cost includes the cost of the cell assembly and the module assembly. According to a study carried out by Galloway & Dustmann (2003), the cell assembly line is a highly automated one, and the module assembly line has a lower automation level. Projects aiming at enhancing automation and cost reductions (lean projects or labor arbitrage projects) could impact this category.

The category with the least impact on the cost of the ZEBRA Battery is the cost of the battery controller which represents 16% of the total cost of a 21 kWh ZEBRA battery. The cost of the controller is similar for any battery, no matter its capacity. Projects that could reduce the cost of the controllers would impact the cost in batteries of small capacities significantly.

Projects that would reduce the cost of the battery and enable a better performance are listed below:

1. **Lower cost β-Alumina ceramic**
   New methods to produce β-alumina tubes for the batteries (D.-G. Lee et al., 2021; Moghadam & Paydar, 2021).
2. **Lower cost of cells by partially replacing Nickel with Iron**
   New design of the battery to enlarge the proportion of Iron and reduce the proportion of Ni in the cathode. (D.-G. Lee et al., 2021; Zhan et al., 2020).
3. **Better and cheaper insulation materials**
   New materials that would reduce the cost of the insulation and reduce thermal losses (Headley et al., 2019; Fantucci et al., 2015).
4. **Alternative mining process to ensure Nickel supply**
   New environmentally friendly methods for Nickel production (Haji & Slocum, 2019; Su et al., 2021).
5. **Efficient recycling process to recover Nickel**
   New methods to recover the nickel from the batteries (Porvali et al., 2020; Zheng et al., 2018).
6. **BMS - Electrical Model for Sodium–Nickel Chloride Batteries**
   New numerical models that enable a more efficient way of managing ZEBRA Batteries (Di Rienzo et al., 2020).

The first three projects (1-3) are the ones that have the most effect on the capital cost of the batteries, and for that reason, are indicated to be managed in-house in Figure 2-21. On the other hand, the last three projects (4-6) represent an improvement that may not affect the capital cost directly, and for that reason, they will be carried out by a third party.

The R&T projects that the 1-ZB roadmap captures are shown in a Gantt Chart in Figure 2-21.

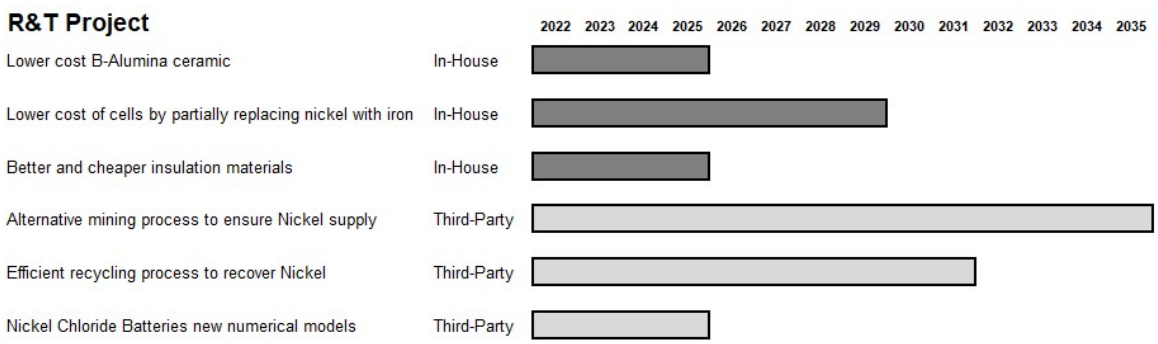


Figure 2-21: 1-ZB Technology Roadmap - Timeline

2.10 Keys Publications, Presentations, and Patents

2.10.1 Keys Publications

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

This article, written in 2001 and cited 312 times according to Google Scholar, explains the operating principle, performance, and production of the sodium-nickel chloride battery. It also describes different applications like electric vehicles, telecommunications, and marine applications.

Advances in ZEBRA batteries, Dustmann (2004).

This article, written in 2004 and cited 289 times according to Google Scholar, describes ZEBRA batteries technology and emphasizes its use for EVs. ZEBRA batteries use salt and nickel as electrodes materials, combined with a solid electrolyte and molten salt. These batteries have a specific energy of 120 Wh/kg and specific power of 180 W/kg. They are suitable for EVs and hybrid electric buses. The ZEBRA battery technology is produced in a plant in Switzerland, which has a production capacity of 2,000 packs/year (equivalent to 40 MWh/year) and a capacity of expansion for 30,000 packs/year.

Evaluating ZEBRA Battery Module under the Peak-Shaving Duty Cycles, Shamim et al. (2021).

This study, published in 2021, was performed by the Battery Materials & System Group from the Pacific Northwest National Laboratory and funded by the Office of Electricity from the U.S. Department of Energy. A battery module based on ZEBRA battery technology (FZSONICK 48TL200) was evaluated for its application in peak-shaving duty cycles in the context of large-scale energy storage applications. First, the module was tested with a full capacity cycle (9.6 kWh) consisting of a charging and discharging process. The battery energy efficiency (discharge vs. charge) was about 90%, and the overall energy efficiency was 80.9%, which includes the auxiliary power used for the BMS and self-heating to maintain the module's internal operating temperature (265 °C). Secondly, for the peak-shaving duty cycle test, holding times were included. Due to the needed self-heating throughout the holding times for a six-hour peak-shaving duty cycle test, the overall module efficiency decreases to 71.8% for 7.5 kWh capacity and 74.1% for 8.5 kWh capacity compared to the full-capacity duty cycle. Lastly, the module showed a capacity degradation rate of 0.0046%/cycle over 150 cycles (one cycle per day) for a long-term cycling test at a six-hour peak-shaving duty cycle with 7.5 kWh energy utilization.

2.10.2 Patents

US 4,546,055: Electrochemical cell, Coetzer & Galloway (1985).

This United States (US) patent is the first one to describe the ZEBRA Battery technology. It was filed in December 1982, and it was obtained on October 8, 1985. The status of this patent is "Expired." It generally describes a rechargeable electrochemical cell with an internal operating temperature of 230°C. The cell components are a molten sodium anode, a molten sodium aluminum halide salt electrolyte, a transition metal chloride cathode, and a solid conductor of sodium ions separator.

The cathode can have different chemical compositions like $FeCl_2$, $NiCl_2$, $CoCl_2$, or $CrCl_2$. The separator is made of β-alumina or Nasicon (sodium super ionic conductor) and acts as a separator, isolating the anode and the electrolyte from each other.

US 8,766,642 B2: Electrochemical cell - General Electric Bogdan et al. (2014)

This US patent enabled GE to be one of the most important ZEBRA batteries producers in the world. It was filed in 2009 and its date of the patent is July 1, 2014. The status of this patent is "Active", and its adjusted expiration is March 28, 2033. This patent describes a modern ZEBRA battery that has a cathode made of $NiCl_2$ and a separator made of β-alumina.

Patents Analysis

A search was conducted in Google for the phrases "ZEBRA battery" or "Sodium Nickel Chloride". The data was extracted and analysed. The results can be seen in Figure 2-22 and Figure 2-23.

Figure 2-22 can be explained the following way. Even though the first patent was filed in 1982, it was studied and developed during the '80s and '90s. At the beginning of 2000, many vital articles were published describing the batteries and explaining their applications, mainly focused on EVs. At the beginning of 2010, two companies, FIAMM (EU) and GE (US), put their efforts into manufacturing and commercializing these batteries. A quick ramp-up of patents started in that period. By then, LIB technology was beginning to consolidate as the best option for EVs. In 2015, GE abandoned the ZEBRA battery project, and in 2017, it joined efforts with a Chinese company to continue developing this technology. Since then, no significant advances have occurred regarding this technology, and the number of patents has been decreasing. The currently available ZEBRA batteries are generally the same as those patented during that period.

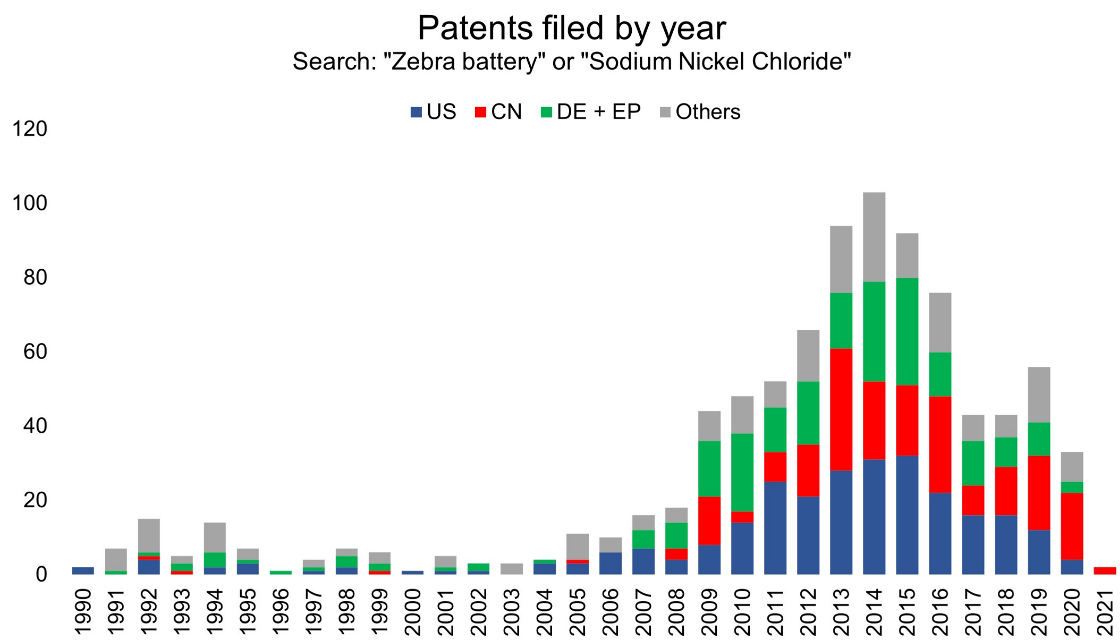


Figure 2-22: Patents filed for ZEBRA battery technology - Timeline. Source: Google.

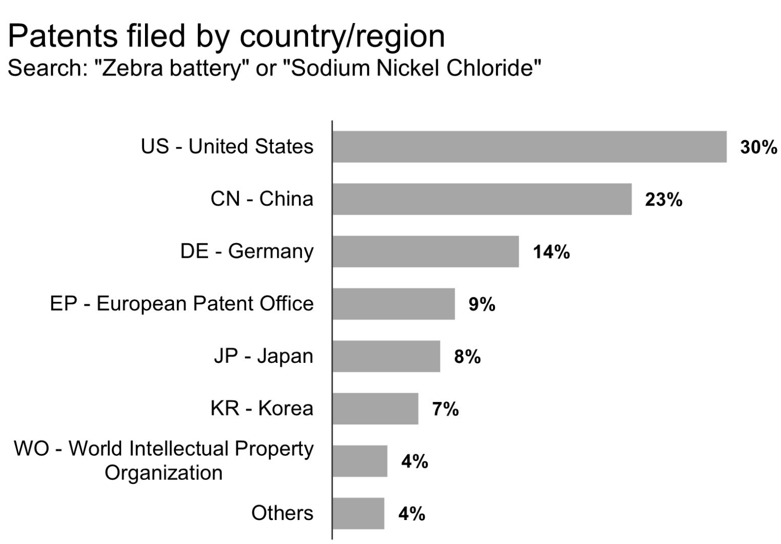


Figure 2-23: Patents filed by country. Source: Google.

2.11 Technology Strategy Statement

The target for ZEBRA battery technology is to develop a battery that costs 480 USD/kWh by 2025 (15% cost reduction of the current price) and 360 USD/kWh (40% cost reduction of the current price) by 2035 by implementing the R&T projects developed in section 2.9. These cost reductions will enable ZEBRA battery technology to increase its market share in energy storage projects by 100% in 5 years. The Technology Strategy Statement Representation can be seen in Figure 2-24.

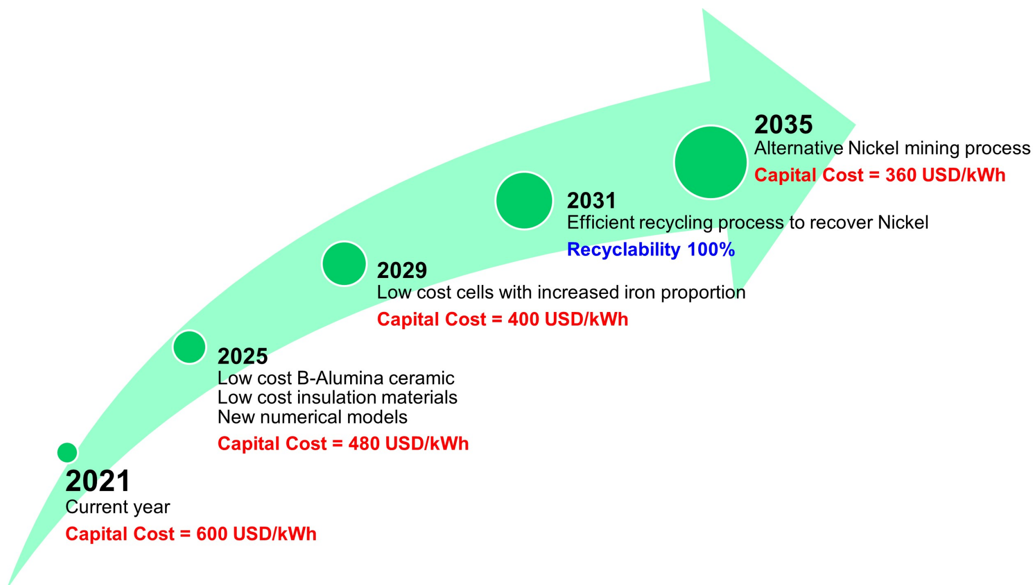


Figure 2-24: ZEBRA battery technology roadmap shown as an Arrow Chart.

Chapter 3

Use Cases and Modelling

In this chapter, applications of electrochemical ESS will be developed and analyzed. In the first part of the chapter, examples of ESS will be shared and explored, the stakeholders involved in these ESS projects will be investigated, and finally, use-cases will be designed. In the second part of this chapter, two models will be developed for three locations, Eastport, Guinea-Bissau, and Texas. The first model is based on Design of Experiments (DOE), and the outcome is a set of configurations of hybrid energy systems formed by VRE sources and modules of batteries. Furthermore, the annual performance of selected cases will be explored. In the second model, the LCA of these selected cases will be analyzed by comparing ZEBRA technology battery modules with LIB technology ones.

3.1 Applications

As explained in Chapter 1, this thesis focuses on ESS that will enable VRE to increase its participation in the electric market. According to a database of ESS, (*Global Energy Storage Projects Database*, 2020) there were more than 1600 energy storage projects worldwide by November 2020. The database contains 28 Energy Storage projects that use Sodium-Nickel-Chloride batteries, which account for 19.68 MW of power rated and 37.14 MWh of capacity. Batteries from FIAMM FZSONICK are used in 50.9% of the cases, while batteries from GE are used in 49.1% of them. The complete list of projects can be seen in Table A.1.

FZSONICK has manufactured and produced ZEBRA Batteries that accumulate more than 1 GWh installed capacity. Still, only a tiny portion of them has been dedicated to Energy Storage purposes, as shown in Figure 3-1.

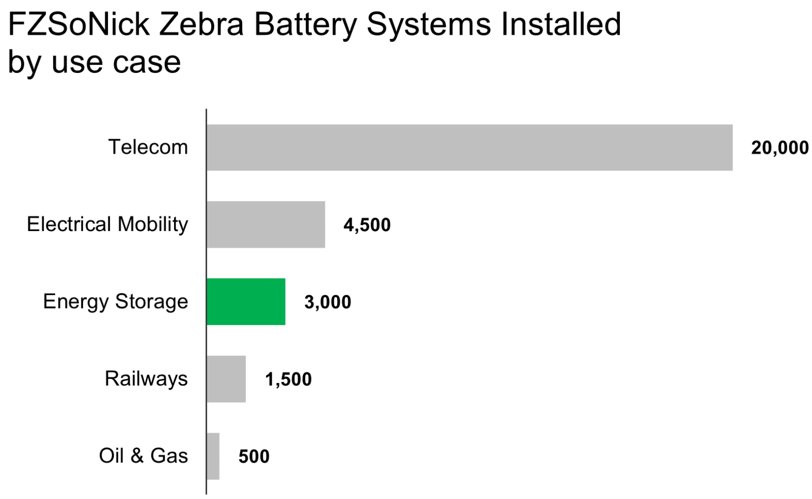


Figure 3-1: FZSONICK batteries installed by use case. Source: fzsonick (n.d.).

3.1.1 Application 1: Utility-scale batteries.

Utility-scales applications are known as "front-of-meter" applications, as shown in Figure 1-8. Storing renewable energy at a large scale requires an electric grid that connects renewable energy sources and the consumers, as mentioned for PHS too.

In general terms, utility-scale batteries would allow:

- Avoiding creating new lines to provide energy during the peak hours that would be idle most of the time (Katz, 2020).
- Maximizing profits for renewable energy projects by enabling energy companies to bid in the electricity market (store energy and sell it when electricity prices are higher) (Spector, 2020).
- Increasing the reliability of the energy systems that rely on variable renewable energy.

- Replacing old fossil fuel-based power plants that provide power during peak hours (Cardwell & Krauss, 2017).
- Reducing the cost of energy for consumers (*HPR enabling significant cost savings*, 2020).

A representation of the power supply and power demand as a system in an OPD is shown in Figure 3-2 and its corresponding OPL is shown in Figure B-9. Only variable renewable energy sources such as wind and solar energy are considered on the power supply side. Different types of demands, such as domestic or industrial, could be considered on the demand side. An electric grid is taken into account to transport the electrical energy from the production location to the demand location. The battery enables the storing process that has two steps, the charging sub-process and the discharging sub-process. In the charging sub-process, the electrical energy is transformed into chemical energy, while in the latter, the chemical energy is transformed back into electric energy.

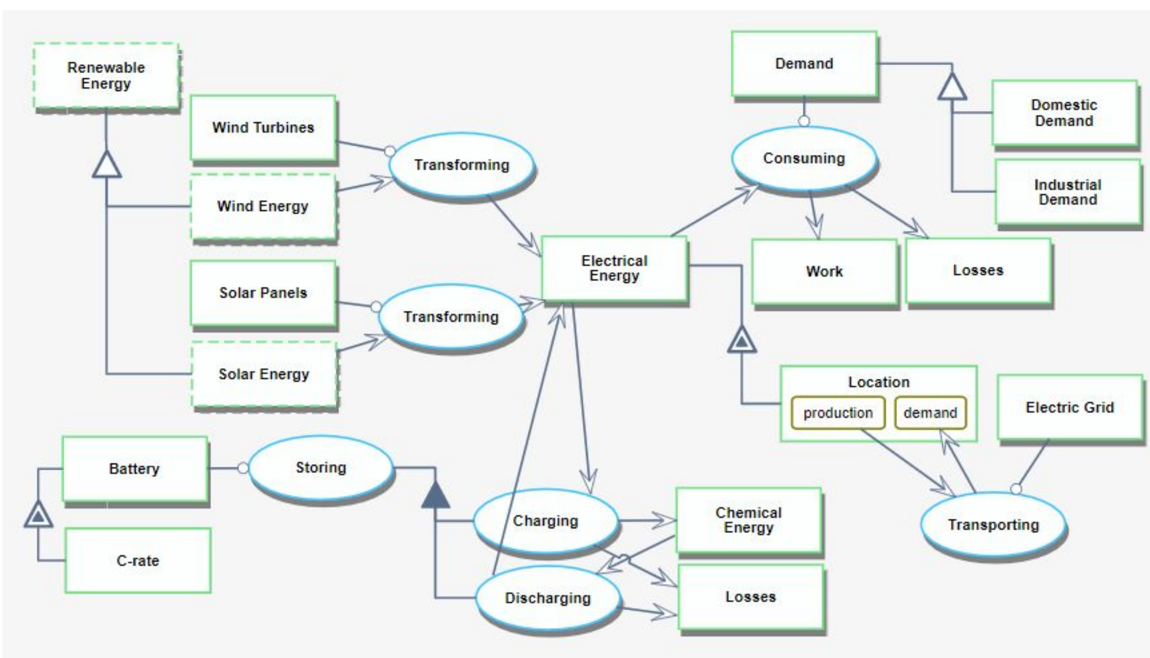


Figure 3-2: Representation of Supply-Demand System for Utility Applications OPD.

LIBs cases

Gateway Energy Storage The Gateway Energy Storage project is located in Otay Mesa, San Diego County, California, and operated by LS Power. The Gateway Energy Storage project is the biggest lithium-ion battery globally, with an installed capacity of 250MW/250MWh utilizing LG Chem Lithium-ion cells. This project tackles the mismatch of demand and supply during the night when no solar energy is produced, mainly caused by the heatwave in California, which increases power demand for air conditioning. It provides a solution by storing energy during off-peak hours with solar production and delivering it to the grid during peak demand. The resulting benefits are an improvement in the reliability of the energy system, cost reduction, and a contribution to California meeting its climate objectives (Collins, 2020).

Figure 3-3: Hornsdale Wind Farm and Power Reserve. Source (*Hornsdale Power Reserve*, 2019). Reproduced with permission of the copyright owner.

Hornsdale Power Reserve The Hornsdale Power Reserve is the second biggest LIB globally, with an installed capacity of 150MW/193MWh utilizing Tesla batteries (Figure 3-3). The project is co-located with Hornsdale Wind Farm, in a significant position of South Australia's electricity transmission network, and is operated by

Neoen. This project tackles the mismatch of demand and supply provided by the Hornsdale Wind Farm (315 MW) that used to cause blackouts in the region. The solution stores energy during off-peak hours with wind energy production and delivers it to the grid during peak demand. The resulting benefits are an improvement in the reliability of the energy system, cost reductions for end-users, and deeper penetration of renewable energy in the network (*Hornsdale Power Reserve*, 2019; A. Lee, 2019).

ZEBRA batteries case

In 2017, FZSONICK ZEBRA batteries (2.8 MWh) were installed on the Greek island of Tilos to support its Hybrid Power System. The island is located in the Aegean Sea, has about 500 inhabitants, and an influx of tourists during the summertime. It produces wind and solar energy, and it is connected to the islands' electric grid in the area. Additionally, the system is managed using a Smart Metering and Demand Site Management platform. As a result of such installation, dependency on fossil fuels was reduced, and the energy system's reliability was improved. Therefore, Tilos illustrates a successful case of the implementation of new technologies related to micro-grids for islands (Kaldellis, 2021).

Sodium-ion batteries case

Sodium-ion batteries have a working mechanism that is similar to LIBs. However, the Na^+ has a larger ionic radius than Li^+, resulting in slower diffusion kinetics and more important volumetric changes during cycles (Mirzaeian et al., 2021).

Currently, only small-scale sodium-ion battery utility applications examples can be found. For instance, a 100 KWh sodium-ion battery power storage plant was built in east China, in Jiangsu Province. This plant was developed by the Institute of Physics of the Chinese Academy of Sciences and the technology firm HiNa Battery. The plant delivers electricity to a Research Center linked to the Institute (*Sodium-ion Battery Power Bank Operational in East China—-Chinese Academy of Sciences*, n.d.).

3.1.2 Application 2: Storing renewable energy at a small scale.

Small-scale applications are known as "behind-the-meter" applications, as shown in Figure 1-8. A simplified version of Figure 3-2 can be seen in Figure 3-4, and its corresponding OPL in Figure B-10. In this case, only solar energy is considered on the power supply side and only domestic demand on the power demand side.

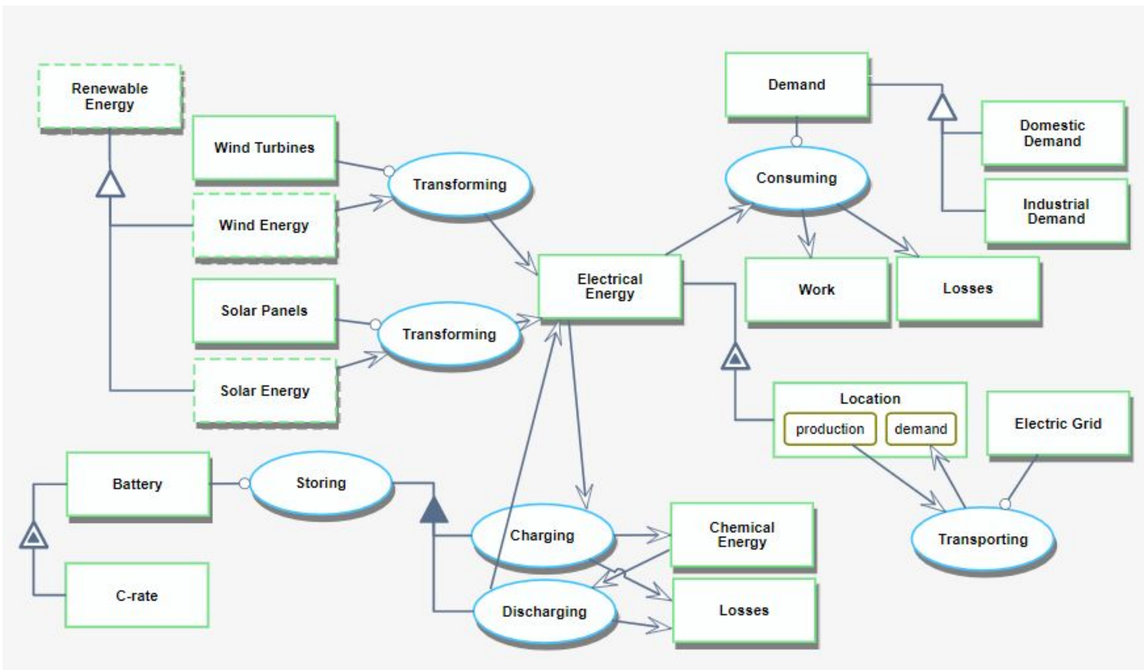


Figure 3-4: Representation of Supply-Demand System for Domestic Applications OPD.

Off-the-grid Local communities

In Woudourou, northeast Senegal, farming communities suffer from food insecurity because they do not have storage for their onion crops. For that reason, Schneider Electric is involved in the Fawrou Remobe project with Entrepreneurs du Monde (EDM)) to provide local farmers with conservation solutions. Refrigerated food granaries enable local farmers to store part of their onion production and sell it at more favorable prices. Schneider Electric provided its expertise in solar micro-grids to EDM to refrigerate storage spaces. This solution was equipped with FZSONICK batteries mod 48TL200 (9.6 kWh each) installed in 2021 to ensure a continuous refrigeration process, especially during the night when there is no sunlight (FZSONICK, 2021; *Fawrou Remobe : food security in Sénégal*, n.d.). Photos of the project can be seen in Figure 3-5.

Figure 3-5: FZSONICK batteries installed in Senegal to store energy from a solar farm to refrigerate a granary. Source:(FZSONICK, 2021). Reproduced with permission of the copyright owner.

3.1.3 Stakeholder Analysis

The stakeholder analysis is shown in Figure 3-6 and Figure 3-7.

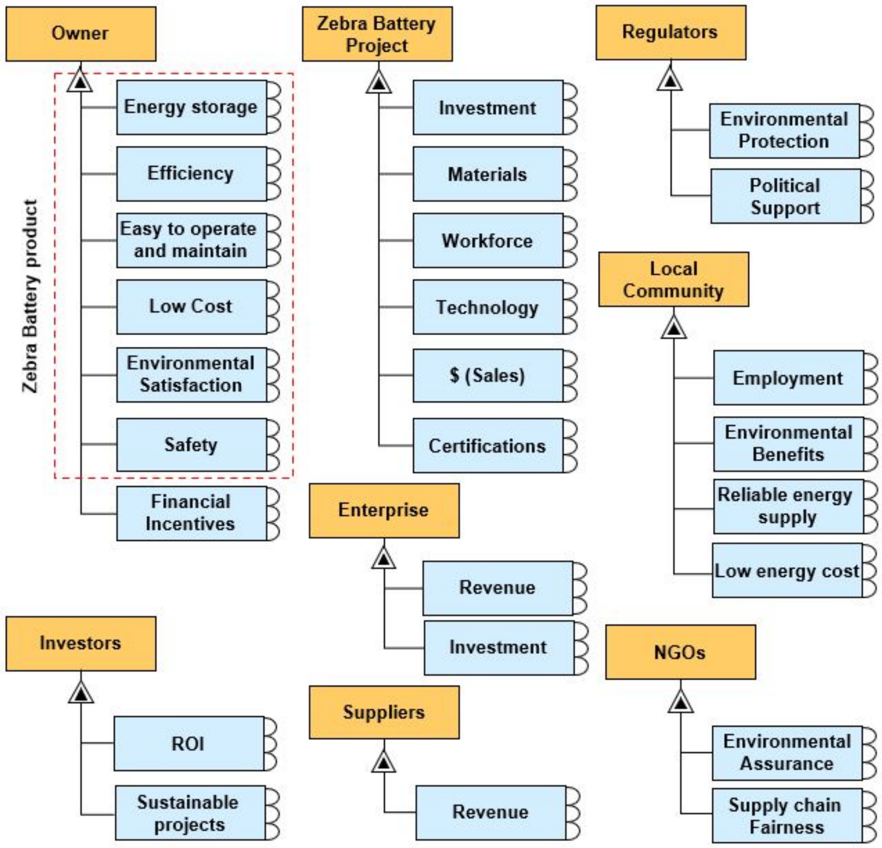


Figure 3-6: Stakeholders' needs. Framework from Crawley et al. (2016).

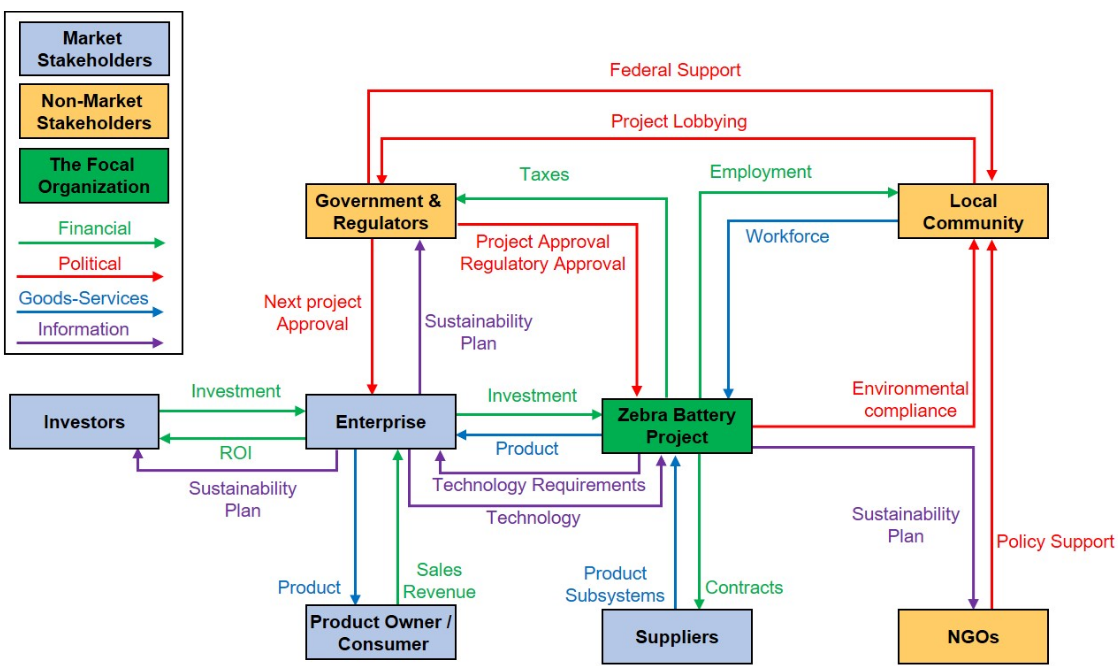


Figure 3-7: SVN. Adapted from Feng et al. (2012).

3.1.4 Use cases definition

After considering the needs of the stakeholders, specific and proper use cases can be elaborated. The use case for utility energy storage is described in Table 3.1. The use case for domestic energy storage is presented in Table 3.2. The purpose of these use cases is to state the mission the product has to accomplish. If the use cases are different, the products may be different too. It may be the product customization to different charge-discharge cycles and use cases that will allow deeper penetration of ZEBRA technology in the Energy Storage market.

Use Case Attribute	Use Case
Title	Satisfies Utility Energy Storage
Identifier	UC_ID_01_utility
Outcome and Performance based Objective	Store energy by providing a service that is: • Capable of storing tens to hundreds of MWh. • Affordable (Capital Cost below 500 USD/MWh). • Reliable (Batteries do not stop working over 15- 20 years) and Efficient (RTE is higher than 80%). • Safe (zero accidents related to energy storage). • No maintenance and easy to install, operate (Friendly interface) and uninstall. • Sustainable (No use of Cobalt or Lithium).
Description	The battery is connected to the system and will be charged when energy is available or cheap according to a software that regulates the process. The software will also compare the production, demand, and energy storage level and deliver the battery's energy when needed. The utility operator will have information about the state of the battery through a friendly interface and will not need to check the battery daily. Weather conditions will not impact the battery performance as refrigeration is not necessary.
Actors	Interface developer. Battery developer. Battery operator. Grid operators. Domestic and Industrial consumers.
Frequency of Occurrence and Utility Priorities	At least once per day. Optimize performance.
Pre-conditions	Battery is discharged.
Post-Conditions	Battery is discharged and with one more cycle of use.

Table 3.1: Use Case: Utility Energy Storage

Use Case Attribute	Use Case
Title	Satisfies Domestic Energy Storage of houses/communities with solar panels
Identifier	UC_ID_02_domestic
Outcome and Performance based Objective	Store energy by providing a service that is: • Capable of storing tens of kWh. • Affordable (Capital Cost below 4000 USD/MWh). • Reliable (Batteries do not stop working over 10 years) and Efficient (RTE is higher than 80%). • Safe (zero accidents related to energy storage). • No maintenance and easy to install, operate (Friendly interface) and uninstall. • Sustainable (No use of Cobalt or Lithium).
Description	The battery is connected to a domestic solar energy system and will be charged with energy when it is available according to a software algorithm. The software will compare the production, demand, and energy storage level and deliver the battery's energy when needed. The battery operator will have information about the state of the battery through a software and will not need to check the battery daily. Weather conditions will not impact the battery performance as refrigeration is not necessary.
Actors	Interface developer. Battery developer. Battery operator. Domestic consumers.
Frequency of Occurrence and Utility Priorities	At least once per day. Optimize performance.
Pre-conditions	Battery is discharged.
Post-Conditions	Battery is discharged and with one more cycle of use.

Table 3.2: Use Case: Domestic Energy Storage

3.2 Modelling - Design of Experiments Approach

The purpose of this section is to model hypothetical hybrid systems of Wind Energy, Solar Energy, and Energy Storage with ZEBRA Technology utilizing a DOE approach to supply as much energy as possible to meet the demand of three substantially different locations that can be seen in Figure 3-8.

Figure 3-8: Map of locations to be modeled. Source: *Google Maps* (n.d.).

3.2.1 Eastport, Maine - USA

In this case, a hypothetical hybrid system of Wind Energy, Solar Energy, and Energy Storage with ZEBRA Technology is modeled to supply renewable energy to meet the electricity demand of the city of Eastport, located in Washington County, Maine, USA (44°54’23", -066°59’26"), whose population was 1,326 inhabitants in 2019 (Bureau, n.d.).

Demand

The hourly demand was extracted from an Urban Building Energy Model (UBEM) created for the city. The details of how it was created can be seen in the paper Ang et al. (2021).

Wind Energy Production

The equation to calculate Wind Power can be seen in Equation 3.1.

$$P_{wind} = \frac{1}{2}\, A\, \rho\, C_p\, V^3 \tag{3.1}$$

Where:

P_{wind} = Wind Power (W)

A = rotor swept area (m^2)

C_p = capacity factor

ρ = air density (kg/m^3)

V = wind velocity (m/s)

The power of one specific wind turbine, the Vestas v117-42, is calculated considering the following data. Hourly wind velocity was extracted from the *Global Wind Atlas* (n.d.) and can be seen in Table A.3. It corresponds to the average wind velocity of the 10% windiest areas in Eastport at the height of 100 m (average 8.46 m/s). The area corresponds to a rotor with a diameter of 117 m. The air density is 1.225 kg/m^3. The capacity factor considered is 31.3% according to Wiser et al. (2018) for the Northeast region in the USA.

The wind energy can be calculated using Equation 3.2. This equation multiples the wind power calculated previously by a time-step of one hour.

$$E_{wind} = P_{wind}\, t \tag{3.2}$$

Solar Energy Production

Hourly Solar Energy was extracted from *Global Solar Atlas* (n.d.) and can be seen in Table A.2 for an industrial power plant of 1 MWp of capacity.

Energy Storage with Batteries

Energy Storage parameters were extracted from fzsonick (n.d.) for a FZSONICK 48TL200 battery. The battery's overall energy efficiency is 80.9% (including the needed auxiliary power to run the battery management system and self-healing process) (Shamim et al., 2021).

Costs

The costs were extracted from the table "Regional variation in Levelized Cost of Electricity (LCOE) and Levelized Cost of Storage (LCOS) for new resources entering service in 2026 (2020 dollars per megawatt-hour)" in *Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021* (2021).

Wind Energy LCOE = 31.45 \$/MWh

Solar Energy LCOE = 31.30 \$/MWh

Batteries LCOS = 121.84 \$/MWh

Calculations

A total of 9 scenarios, with 6 variants each, were created. That means that a total of 54 cases were calculated by changing 3 variables:

- # Wind Turbines (4.2 MW each)
- # Solar Plants (1 MWp each)
- # ZEBRA batteries (9.6 kWh each)

The list of scenarios is the following:

- 100% Wind Energy - 2 wind turbines of 4.2 MW
- 100% Wind Energy - 3 wind turbines of 4.2 MW
- 100% Wind Energy - 4 wind turbines of 4.2 MW
- 100% Solar - 10 MWp installed
- 100% Solar - 20 MWp installed
- 100% Solar - 30 MWp installed
- Mix - 10 MWp solar + 3 wind turbines of 4.2 MW
- Mix - 20 MWp solar + 2 wind turbines of 4.2 MW
- Mix - 30 MWp solar + 1 wind turbines of 4.2 MW

The variants for each scenario, which are listed below, are related to Energy Storage Capacity.

- no batteries
- 4.8 MWh
- 9.6 MWh
- 14.4 MWh
- 19.2 MWh
- 24.0 MWh

The following equations are necessary intermediate calculations.

$$E_{produced} = E_{wind} + E_{solar} \tag{3.3}$$

$$E_{produced} = E_{consumed\ directly} + E_{Charged\ in\ batteries} + E_{surplus} \tag{3.4}$$

$$E_{Charged\ in\ batteries} = E_{Discharged\ by\ batteries} + E_{Losses} \tag{3.5}$$

$$E_{supplied\ to\ the\ system} = E_{consumed\ directly} + E_{Discharged\ by\ batteries} \tag{3.6}$$

The performance of these cases is evaluated by calculating two different variables: Energy cost in USD (Equation 3.7) and Electric Demand met in percentage (Equation 3.8).

$$Cost_{Energy} = LCOE_{wind}\ E_{wind} + LCOE_{solar}\ E_{solar} + LCOS_{Batteries}\ E_{Discharged\ by\ batteries} \tag{3.7}$$

$$Demand\ met = \frac{E_{supplied\ to\ the\ system}}{E_{Demand}} \tag{3.8}$$

Results

The results of the calculations for Eastport, Maine, are shown in Figure 3-9. Under this specific scenario, it is possible to see that the configurations that achieve the lowest costs and the highest value of demand met are those based on Wind Energy, as they are on the Pareto Frontier. One case (highlighted in red) on the Pareto Frontier was selected to explore its behavior. This case has a configuration of 3 wind turbines with an installed capacity of 12.6 MW and an Energy Storage capacity of 9.6 MWh. One crucial assumption in this scenario is the existence of an electric network in the area that would distribute the energy to all domestic and industrial consumers. This system can satisfy 75.4% of the Electric Demand in Eastport with an annual cost of 1.16 MUSD. Additionally, this system has an energy surplus of 28.2% of its produced energy which could be managed in two different ways. If the city of Eastport has an electric grid that connects it with other demand centers, this surplus could be sold (not considered in this analysis) in the electric market. If the city is isolated, the wind turbines should be shut down to avoid the surplus, destabilizing the electric network. This surplus exists because of the mismatch of the demand and the produced energy, mainly during the spring and summer, as seen in Figure 3-10 and Figure 3-12. The Energy demand cannot be met by the produced energy during the winter as seen in Figure 3-10 and Figure 3-11. That could be interpreted as a need to import electricity from the grid (if connected to other electricity suppliers) or to burn fossil fuels to generate electricity and/or heat. This great difference among seasons is attributed to the heating system required during cold weather. The use of batteries allows the system to meet 74.6% of the demand against the 71.1% met by the same system with no batteries (+3.5%).

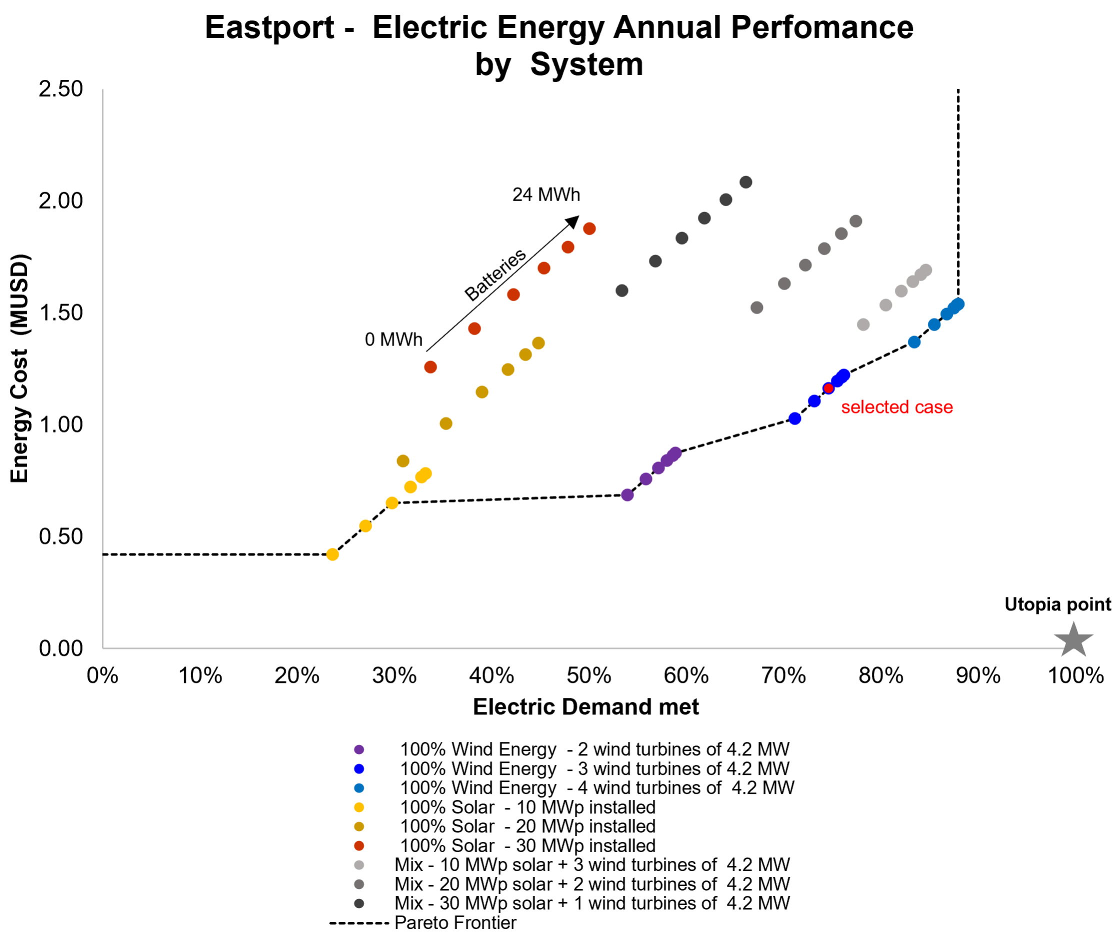


Figure 3-9: Eastport, Maine - Tradespace for Total Energy Cost vs. Electric Demand Met.

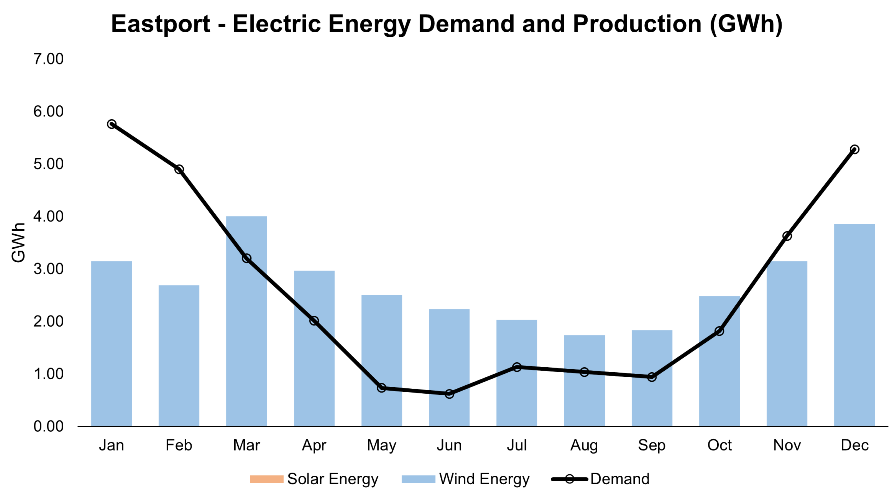


Figure 3-10: Eastport, Maine - Annual Electric Demand and Production for the Selected Case.

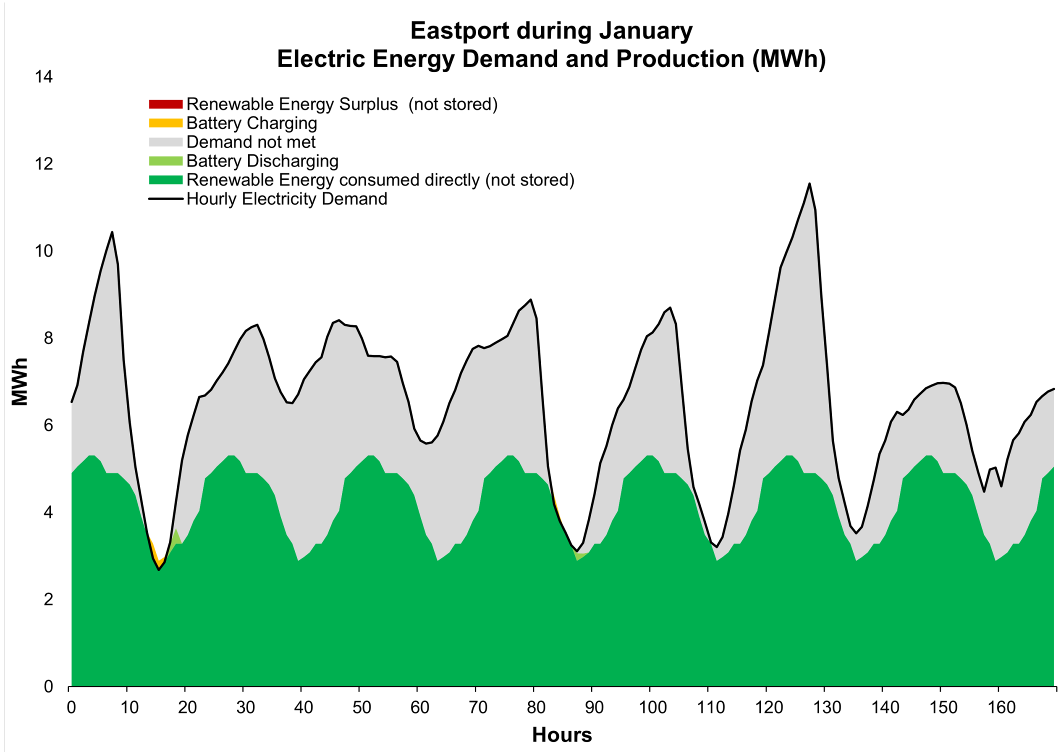


Figure 3-11: Eastport, Maine - Selected Case Performance during January.

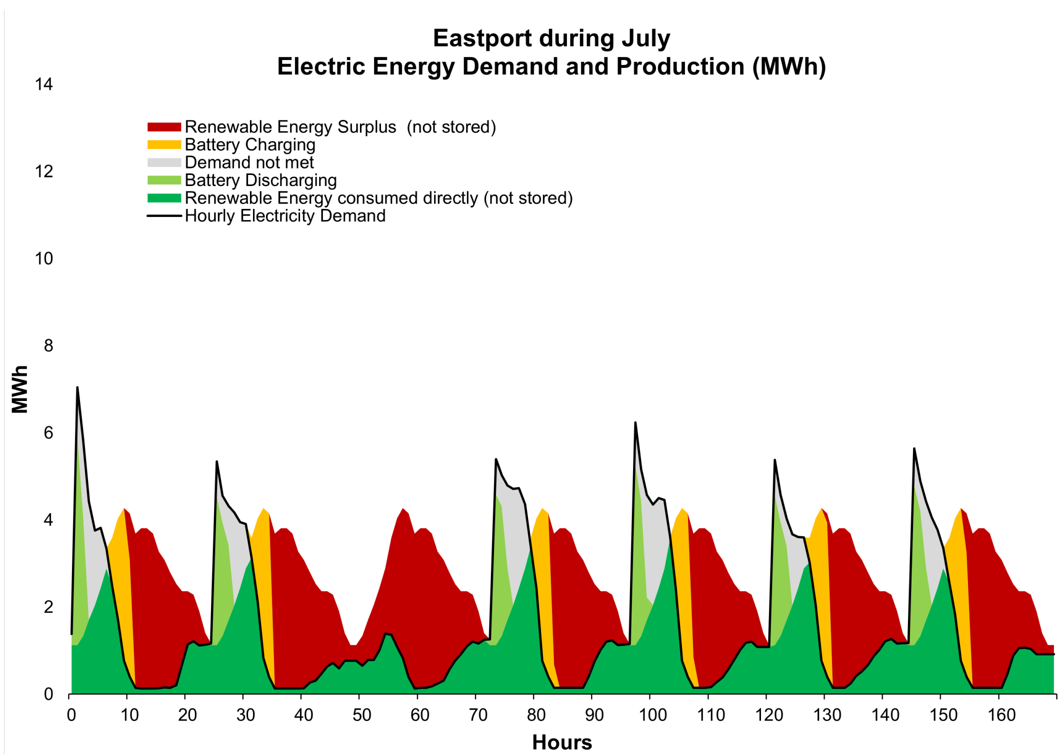


Figure 3-12: Eastport, Maine - Selected Case Performance during July.

3.2.2 Guinea-Bissau

In this case, a hypothetical hybrid system composed of Solar Energy and Energy Storage with ZEBRA Technology is modeled to supply with renewable energy the energy needed to satisfy the demand of the country of Guinea-Bissau in Africa, whose population was about 1.921 million inhabitants in 2019 (*WDI - Home*, n.d.).

Demand

The hourly demand was extracted from Adeoye & Spataru (2019).

Solar Energy Production

Hourly Solar Energy was extracted from *Global Solar Atlas* (n.d.) and can be seen in Table A.4 for an industrial power plant of 1 MWp of capacity.

Calculations

Following the same procedure described in subsection 3.2.1, a total of 5 scenarios, with 5 variants each, were created. Therefore, a total of 25 cases were calculated by changing 2 variables:

- # Solar Plants (1 MWp each)
- # ZEBRA batteries (9.6 kWh each)

The scenarios considered are listed below:

- 100 MWp solar
- 125 MWp solar
- 150 MWp solar
- 175 MWp solar
- 200 MWp solar

The variants for each scenario, which are listed below, are all related to Energy Storage Capacity:

- no batteries
- 96 MWh
- 192 MWh
- 288 MWh
- 384 MWh

Results

The results of the calculations are shown in Figure 3-13. One case (highlighted in red) on the Pareto Frontier was selected to explore its behavior. This case has a configuration of 150 MWp of Solar Energy and an Energy Storage capacity of 288 MWh. Wind energy was not included as an option, as it would require an electric network in the area to distribute the energy to all domestic and industrial consumers. This is not the case as only 31% of the population of Guinea-Bissau has access to electricity (*Access to electricity - Guinea-Bissau*, n.d.). The outcome of this modeling represents the sum of many small-scale hybrid systems for local communities. The selected system can satisfy 74.7% of the Electric Demand in Guinea-Bissau with an annual cost of 17.61 MUSD. Additionally, this system has an energy surplus of 9.3% of its produced energy. As this surplus cannot be sold in the electric market (distributed in isolated microgrids), it is essential to keep its value low. This surplus is the result of the mismatch of the demand and the produced energy throughout the day, as seen in Figure 3-15 and Figure 3-16, and throughout the year, as seen in Figure 3-14. The big difference among seasons is attributed to the rainy season (between June and September) that causes a reduction of the sun hours (*Bissau climate: Average Temperature*, n.d.). As the energy demand cannot be met 100% by the produced energy, there is still a need to burn fossil fuels to generate electricity. The use of batteries allows the system to satisfy 74.7% of the demand against only 45.2% for the same system with no batteries (+29.5%). However, it is essential to mention that these calculations were done considering that the solar panels are clean and free of dust. Dust aerosols in the region will negatively impact the efficiency of the panels if proper maintenance is not taken into account (Deardorff et al., n.d.).

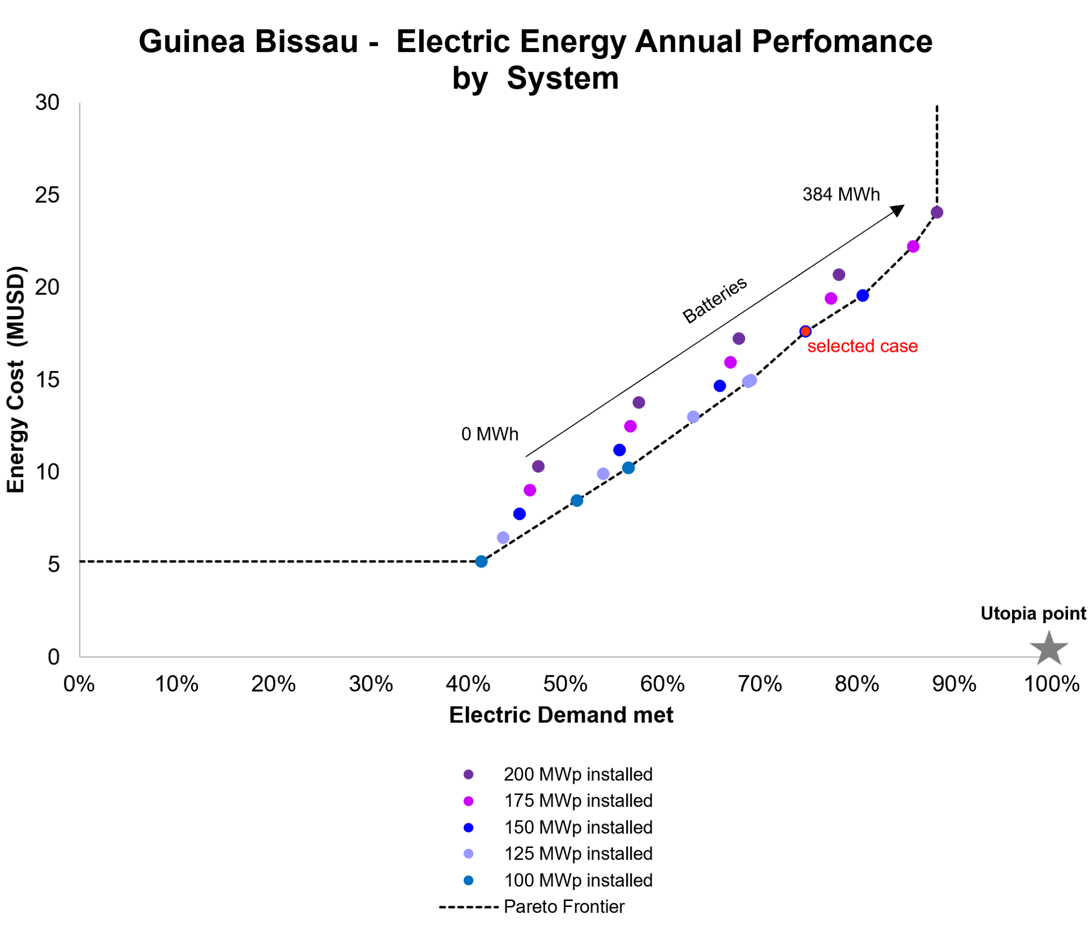


Figure 3-13: Guinea-Bissau - Tradespace for Total Energy Cost vs. Electric Demand Met.

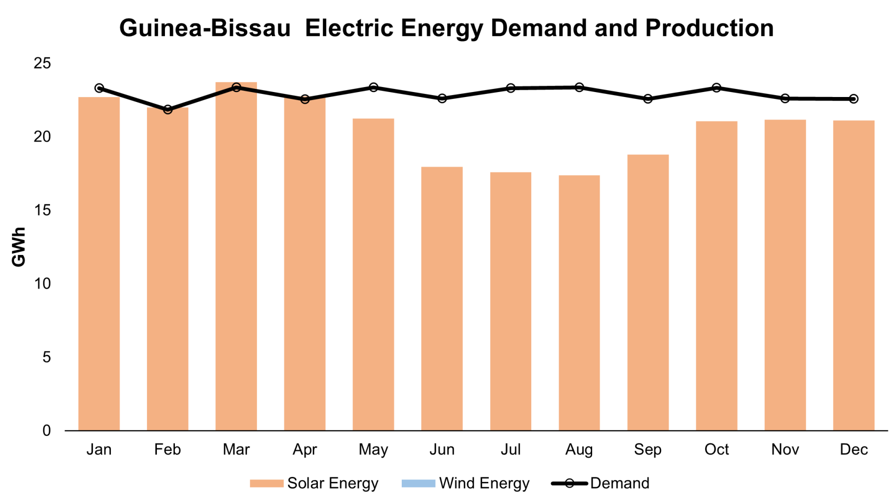


Figure 3-14: Guinea-Bissau - Annual Electric Demand and Production for the Selected Case.

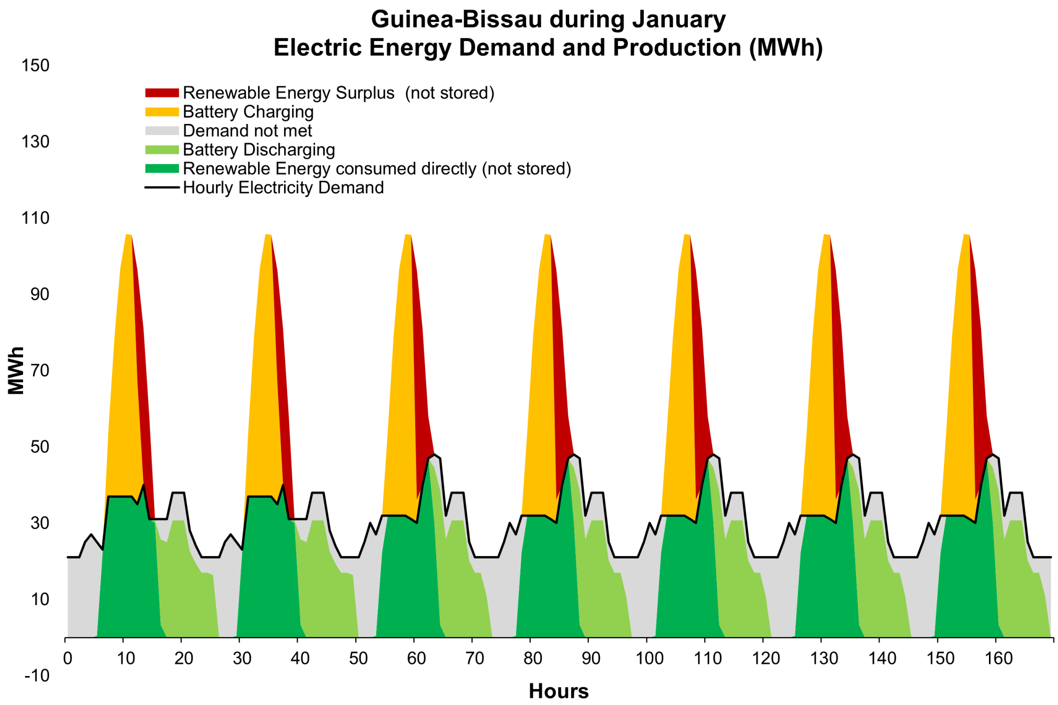


Figure 3-15: Guinea-Bissau - Selected Case Performance during January.

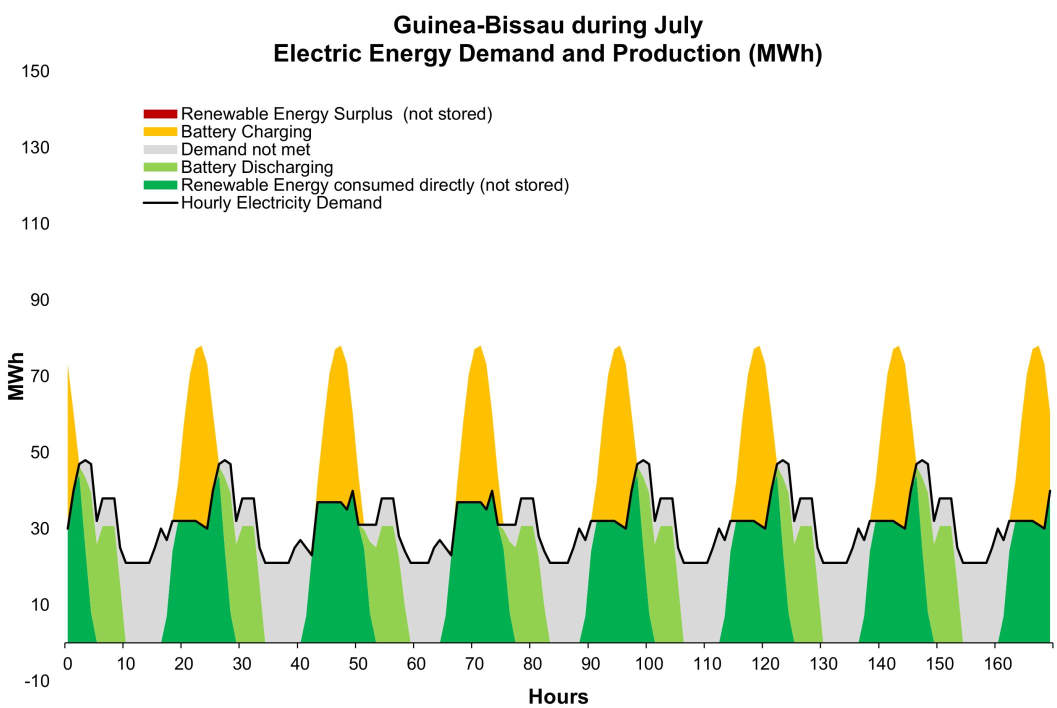


Figure 3-16: Guinea-Bissau - Selected Case Performance during July.

3.2.3 Texas - USA

In this case, a hypothetical hybrid system, composed of Wind Energy, Solar Energy, and Energy Storage with ZEBRA Technology, is modeled to supply renewable energy to the electric demand of the state of Texas (USA), whose population was 29 million inhabitants in 2019 (Bureau, n.d.).

Demand

The hourly demand was extracted from *Hourly Load Data Archives* (n.d.) for the year 2019. The data for 2020 was not considered to avoid the influence of the Covid-19 pandemic.

Wind Energy Production

Hourly Wind velocity was extracted from *Global Wind Atlas* (n.d.) and can be seen in Table A.5. It corresponds to the average wind velocity of the 10% windiest areas in Texas at the height of $100\,m$ (average $8.72\,m/s$). The area corresponds to a rotor with a diameter of 117 m. The air density is $1.225\,kg/m^3$. The capacity factor considered is 33.0% according to Wiser et al. (2018) for the Southeast region in the USA. The wind energy can be calculated using Equation 3.2.

Solar Energy Production

Hourly Solar Energy is extracted from *Global Solar Atlas* (n.d.) and can be seen in Table A.6 for an industrial power plant of 1 MWp of capacity.

Calculations

Following the same procedure described in subsection 3.2.1, a total of 11 scenarios, with 5 variants each, were created. That means that a total of 55 cases were calculated by changing 3 variables:

- # Wind Turbines (4.2 MW each)
- # Solar Plants (1 MWp each)

- # ZEBRA batteries (9.6 kWh each)

The list of scenarios is the following:

- 100% Wind - 200 GW Wind
- 100% Wind - 150 GW Wind
- 100% Wind - 100 GW Wind
- 100% Solar - 350 GW
- 100% Solar - 250 GW
- 100% Solar - 150 GW
- 150 GW Solar + 150 GW Wind
- 150 GW Solar + 50 GW Wind
- 50 GW Solar + 150 GW Wind
- 50 GW Solar + 50 GW Wind
- 30 GW Solar + 118 GW Wind [1]

The variants for each scenario are related to Energy Storage Capacity. The list of variants is the following:

- no batteries
- 48 GWh
- 96 GWh
- 144 GWh
- 192 GWh

Results

The results are shown in Figure 3-17. The configurations on the Pareto Frontier are based 100% on wind energy or are a hybrid system of wind energy and low participation of solar energy. One case (highlighted in red) on the Pareto Frontier was selected to explore its behavior. This case has a configuration with an installed capacity of 118 GW of wind energy and 30 GW of solar energy, and an Energy Storage

[1] The author created this scenario while looking for a better configuration performance than the case 100% Wind - 150 GW Wind.

capacity of 96 GWh. One crucial assumption in this scenario is the existence of an electric network in the area that would distribute the energy to all the domestic and industrial consumers. This system can supply 82.6% of the electricity to meet the demand in Texas with an annual cost of 16 Billion USD.

Additionally, this system has an energy surplus of 26.2% of its produced energy. That can have two different interpretations for this case. If Texas has an electric grid that connects it with other states, this surplus could be sold (not considered in this analysis) in the electric market. If Texas is electrically isolated, the wind turbines should be shut down to avoid destabilizing the electric network. This surplus exists because of the mismatch of the demand and the produced energy, as seen in Figure 3-18 and Figure 3-19. The Energy demand cannot be met 100% by the produced energy during the summer as seen in Figure 3-20. That could be interpreted as a need to import electricity from the grid (if connected to other electricity suppliers) or burn fossil fuels to generate electricity. This significant difference among seasons is attributed to the air conditioner systems activity during the summer.

Currently, the Electric Reliability Council of Texas (ERCOT) is not entirely detached from other grids. It has three ties to Mexico and two ties to the Eastern US electric grid. Nevertheless, it remains outside the control of the Federal Energy Regulatory Commission, which regulates interstate electric transmission (*Secession and power outages: Why does Texas have its own electrical grid?*, 2021). That is to say, electrical transmission among Texas and other states is not a regular practice. This condition was in evidence in February 2021, when the state underwent blackouts due to a peak of demand during severe winter storms (*ERCOT Blackout 2021*, 2021). The electric transmissions with other states would allow ERCOT to be more robust and increase its renewable energy supply, as it would be easy to sell the energy surplus and buy electricity during peaks of demand.

The use of batteries allows the system to meet 82.6% of the demand against the 77.6% of the same system with no batteries (+5.0%). This hypothetical scenario requires around 10 million batteries (FZSONICK 9.6 kWh). This could be possible by a mixture of power storage plants and at least 1 or 2 batteries in each residence.

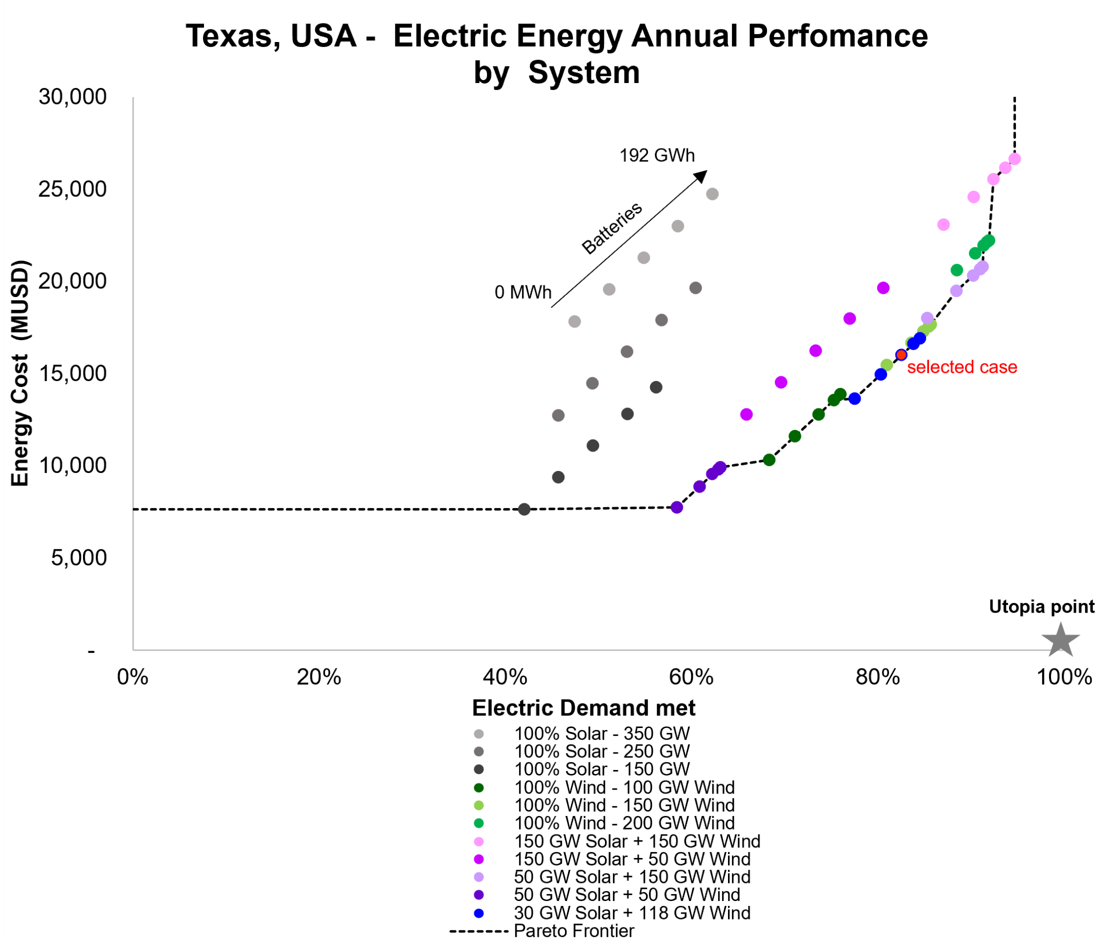


Figure 3-17: Texas - Tradespace for Total Energy Cost vs. Electric Demand Met.

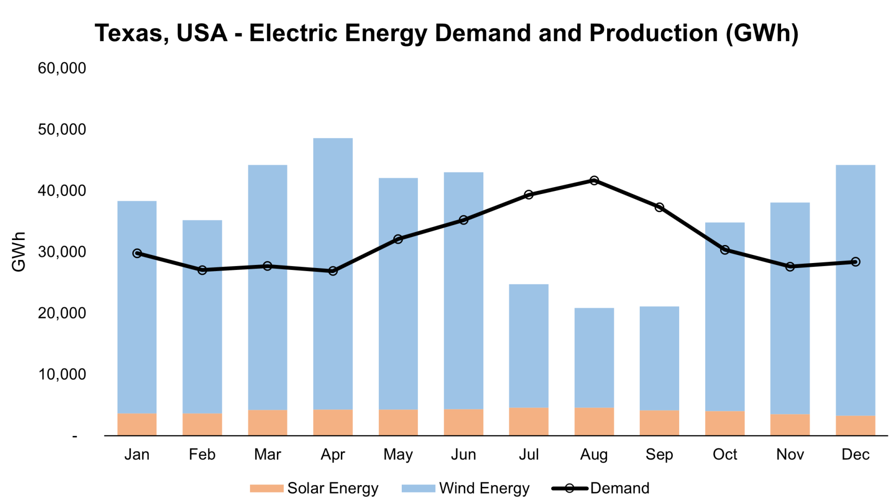


Figure 3-18: Texas - Annual Electric Demand and Production for the Selected Case.

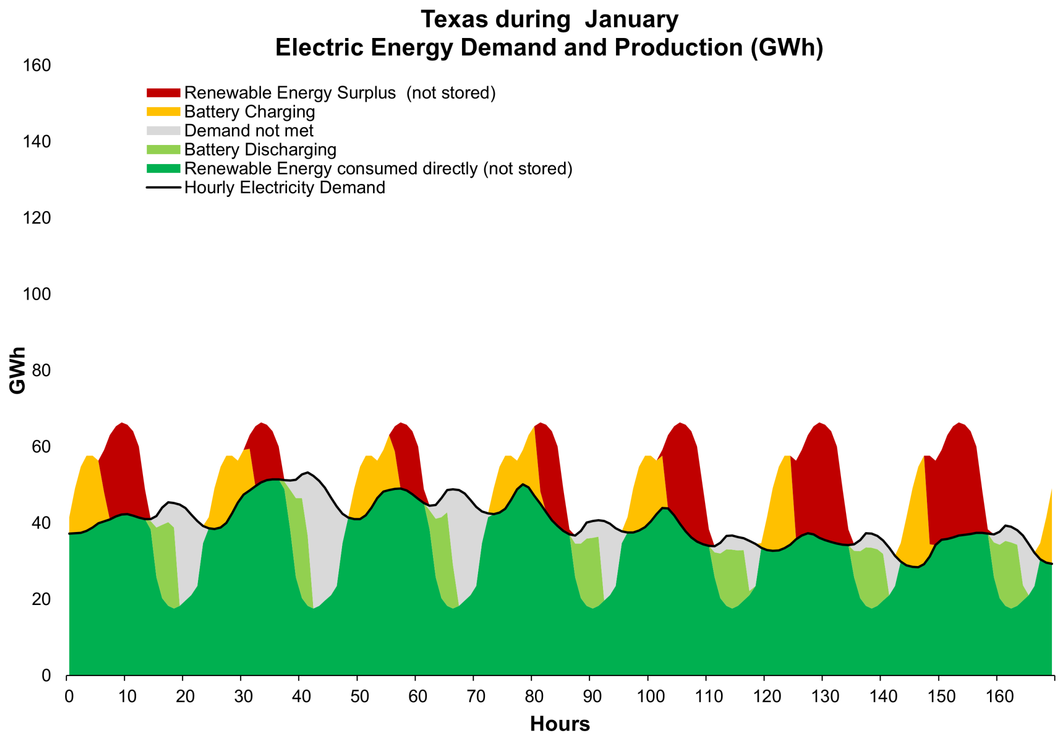


Figure 3-19: Texas - Selected Case Performance during January.

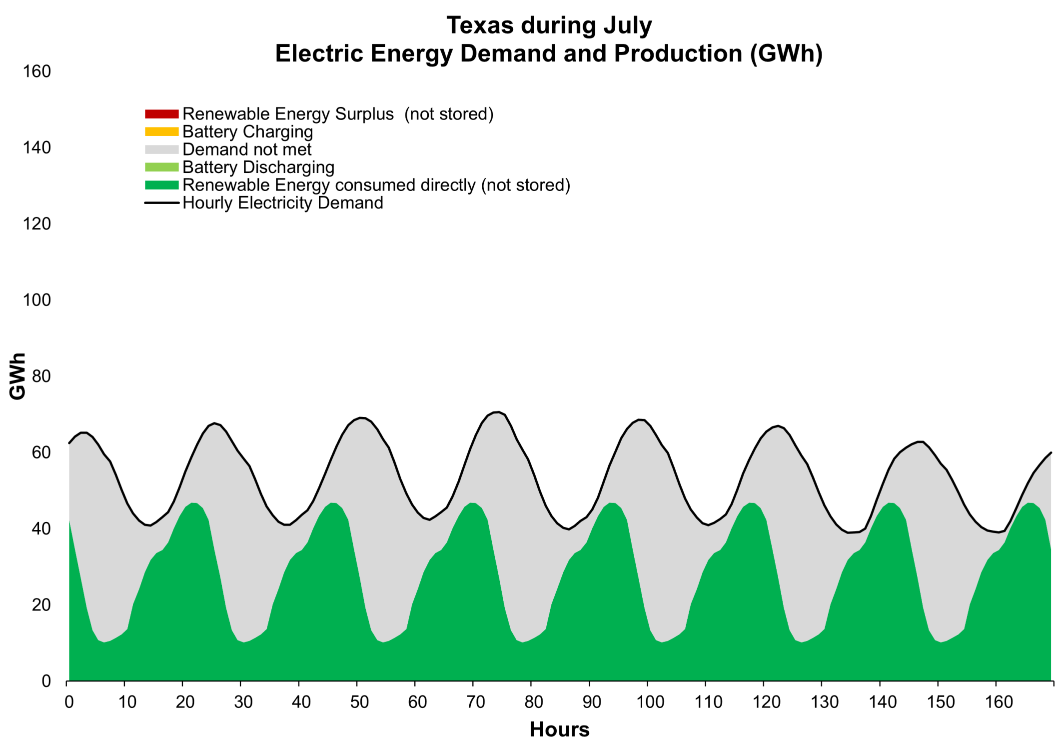


Figure 3-20: Texas - Selected Case Performance during July.

3.3 Modelling - Life Cycle Analysis and comparison with LIBs.

The output from the previous analysis is suitable to model how much Energy Storage Capacity should be installed to achieve a hybrid system that can rely mainly on VRE. The analysis was done for one full year to capture seasonality. The LCOS utilized was obtained from the literature for the category "Battery Storage." For that reason, the model is not appropriate to compare the system's performance over its whole life cycle or compare it with different batteries technologies.

3.3.1 Variables analysis

The following variables will be analyzed for a LCA to compare ZEBRA and LIB technologies:

- Degradation Rate of Batteries, Solar Panels and Wind turbines.
- Capital Cost
- Operation Cost
- Decommissioning Cost

Degradation Rate and Performance

A degradation factor of 0.5%/year was considered for solar panels according to Jordan & Kurtz (2013).

A degradation factor of 1.5%/year was considered for wind turbines according to Staffell & Green (2014).

ITP Renewables has the first battery comparison test site in the world, which was funded by the Australian Renewable Energy Agency. It provides independent data about the performance of different batteries according to a standardized test. The results can be seen in *Reports – Lithium Ion Battery Test Centre* (n.d.).

According to this report, two LIBs with NMC technology, LG Chem RESU HV and Tesla Powerwall 2, show a significant reduction in State of Health (SOH), which is the ratio of the energy delivered at a specific capacity test by the energy produced at the first one. For the LG Chem RESU HV battery, 60% of its SOH is observed at 3,330 cycles with an extrapolation after acquiring data for 1500 cycles approximately. For the Tesla Powerwall 2 battery, 60% of its SOH is observed at 3,680 cycles with an extrapolation after acquiring data for more than 1500 cycles. Based on this information, the assumption for LIBs in this study is that 60% of its SOH will be reached after 3500 cycles, which is equal to 0.0114% per cycle. The degradation process of LIBs at different conditions is a matter of current studies.

Also, an FZSONICK 48TL200 battery is being tested at the moment this study is written. 100% of its SOH is observed at 500 cycles. No degradation has been observed in this test yet. The same battery was studied in Shamim et al. (2021) and exhibited a capacity degradation rate of 0.0046% per cycle over 150 cycles (equivalent to 150 days) for peak-shaving applications, for a long-term cycling test at a six-hour peak-shaving duty cycle at 80% DOD.

Although batteries can be used beyond 80% of ther capacity, this value is a benchmark that manufacturers reference to indicate the end of life in the datasheets (Preger et al., 2020). In this analysis, batteries will be replaced once the degradation process results in values below 80% of capacity, as the degradation process would be accelerated after that point.

Capital Cost

The price of the products is different. For LIBs used in utility applications, a value of 380 USD/kWh is assumed in Cole & Frazier (2020). For ZEBRA batteries, a cost of 600 USD/kWh is assumed according to FZSONICK sources.

Operative Cost

An O&M fixed cost of 10 USD/kW-year is considered for both technologies, which has been taken from Mongird et al. (2019).

Decommissioning Cost

Decommissioning Cost is assumed as 10% of the initial capital investment. This would include the cost of the final disposal of the batteries, which could be the battery's transport to a recycling plant. Once at the recycling plant, the process of recycling is profitable due to the high cost of the recovered materials (Ma et al., 2018).

3.3.2 Eastport selected case LCA

Annual characterization of charge/discharge cycles.

In Figure 3-21 it is possible to see the daily SOC for an entire year. The batteries will not have enough available VRE to achieve a SOC of 100% during the winter when the electricity demand is the highest in the year due to the cold weather. In Figure 3-22, the probabilistic distribution of the cycles is shown in a histogram. From the cluster of cycles that belong to values below 20% of SOC, 46 of the 64 data points in the cluster have values equal to zero. That is to say that during a whole year, for this specific configuration, batteries will have 319 cycles, where 277 of them will have SOC greater than 80%.

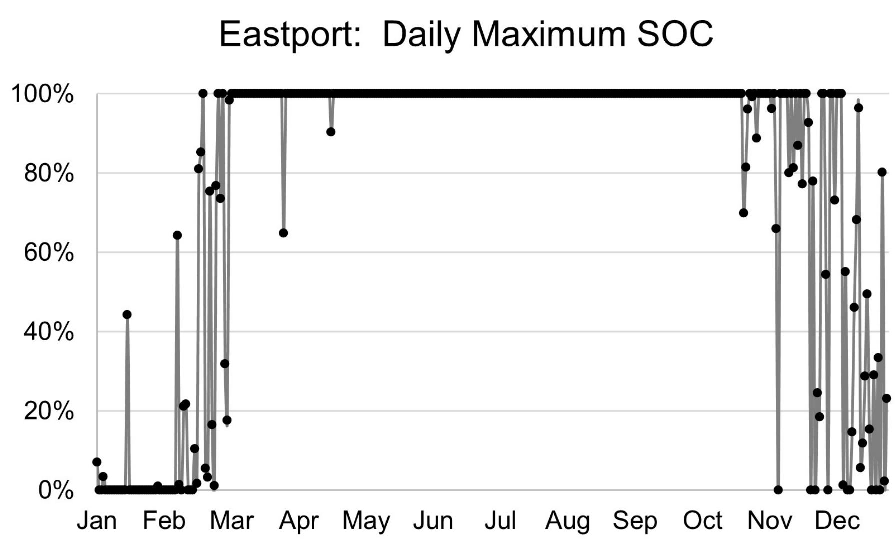


Figure 3-21: Eastport, Maine - Daily Maximum SOC.

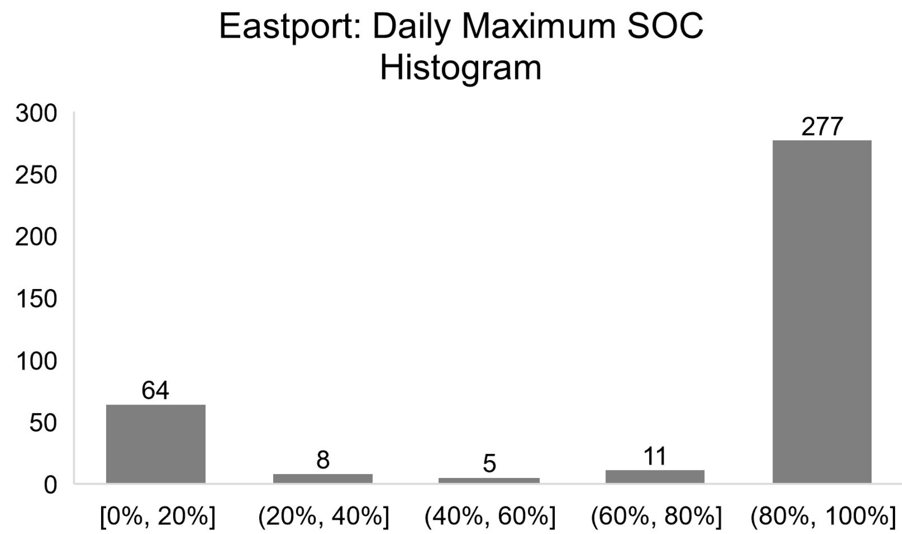


Figure 3-22: Eastport, Maine - Daily Maximum SOC (Histogram).

Technology comparison

Based on the number of effective cycles per year, average capacity efficiencies by year were calculated for ZEBRA batteries and LIBs. The results are shown in Table 3.3 with the capacity efficiencies for wind turbines and solar panels.

year	Wind Turbines	Solar	ZEBRA	LIBs
1	1	1	1	1
2	0.985	0.995	0.9853	0.9635
3	0.97	0.99	0.9707	0.9271
4	0.955	0.985	0.956	0.8906
5	0.94	0.98	0.9413	0.8542
6	0.925	0.975	0.9266	0.8177
7	0.91	0.97	0.912	1 (* new)
8	0.895	0.965	0.8973	0.9635
9	0.88	0.96	0.8826	0.9271
10	0.865	0.955	0.8679	0.8906
11	0.85	0.95	0.8533	0.8542
12	0.835	0.945	0.8386	0.8177

Table 3.3: Eastport, Maine - Capacity efficiency table. (*) A replacement of all LIBs is considered in year 7.

For this analysis, the same model explained in section 3.2 will be calculated for each of the years in Table 3.3. The difference in costs between two ESS of the same capacity (selected case) but different battery technologies is analyzed with the NPV methodology to capture the value of money over time. An IRR of 10% is considered.

The difference of energy delivered by the batteries is calculated. This exercise assumes that the energy difference will be bought from the grid in case it is negative. It is worth mentioning that this assumption is very simplistic as in real cases, if the ESS does not deliver the energy that agreed by contract, the operator can be penalized. The value of energy considered is 0.1616 USD/kWh for the state of Maine (*ElectricChoice.com – Compare Electricity Rates, Plans, and Providers*, n.d.).

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Δ Capex [k USD]	-2112						3648						
Δ Opex [k USD]		0	0	0	0	0	0	0	0	0	0	0	0
Δ Decommissioning cost [k USD]							365						-211
Δ Energy supplied by bat. [GWh]		0	0	0	0	0	0	0	0	0	0	0	0
Δ Cost imported Energy [k USD]		0	3	5	8	11	14	-11	-9	-6	-3	0	3
Cash Flow [k USD]	-2112	0	3	5	8	11	4027	-11	-9	-6	-3	0	-208
Discounted Cash flow [k USD]	-2112	0	2	4	6	7	2273	-6	-4	-2	-1	0	-66
Cum. Disc. Cash flow [k USD]	-2112	-2112	-2110	-2106	-2100	-2093	180	174	170	168	167	167	100
NPV [k USD]	**100**												

Figure 3-23: Eastport, Maine - Technology Comparison NPV.

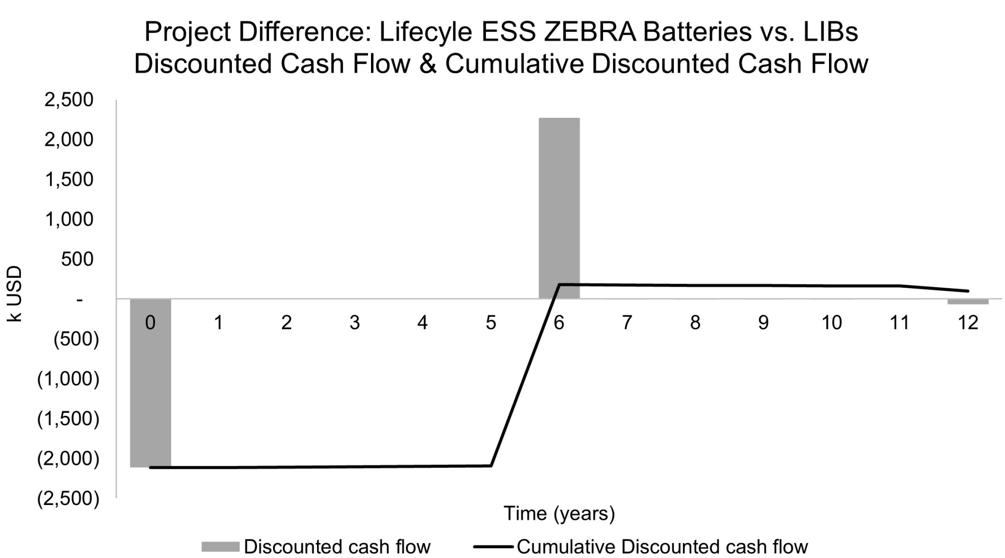


Figure 3-24: Eastport, Maine - Technology Comparison Cash Flow

In Figure 3-23 and Figure 3-24 it is possible to see the comparison of technologies for the selected case of Eastport, an ESS of 9600 kWh. The result is a positive NPV of 100 kUSD in favor of the ZEBRA battery technology (at current prices). The way the calculation is done, a positive number means that the preferred technology is ZEBRA. However, this value must be considered insignificant compared to the initial investment of both technologies for this project. An initial investment of 5.76 MUSD is needed to deploy the project with ZEBRA Technology and 3.65 MUSD with LIBs.

Figure 3-25 shows a sensitivity analysis performed by changing the following variables related to the FOMs analyzed in section 2.4:

- ZEBRA Batteries Capital Cost 540 USD/kWh (-10% base case)
- ZEBRA Batteries Operation Cost 9 USD/kW-year (-10% base case)
- ZEBRA Batteries Degradation Rate = 0 (no degradation)
- ZEBRA Batteries Decommissioning Cost 9% of initial capital investment(-10% base case).

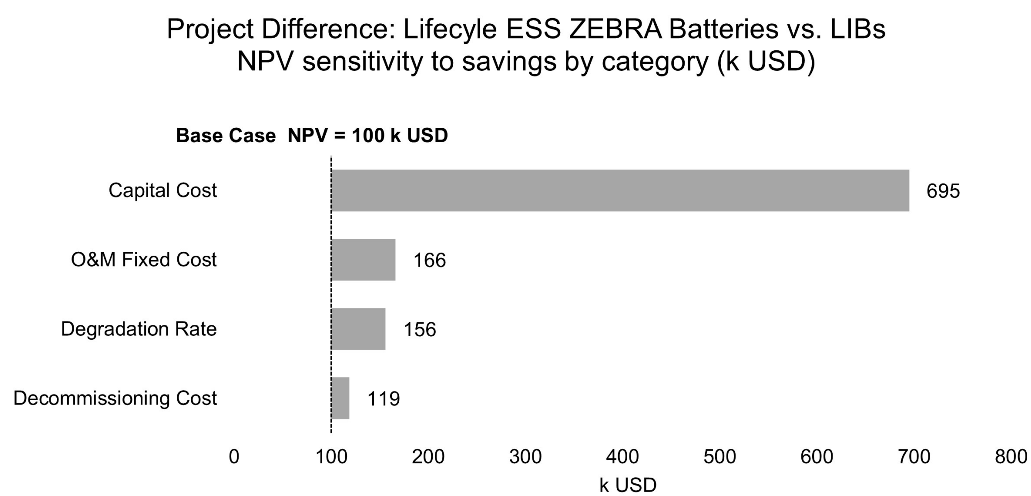


Figure 3-25: Eastport, Maine - Technology Comparison NPV Sensitivity Analysis

It is possible to see that the variable that impacts the NPV the most is the Cost of Capital. That is why this variable was prioritized in section 2.9.

The same model was tested with an IRR (discount rate) of 5%, and the result was an NPV of 780 kUSD in favor of the ZEBRA technology.

3.3.3 Guinea-Bissau selected case LCA

Annual characterization of charge/discharge cycles.

In Figure 3-26 it is possible to see the daily SOC for an entire year. It can be seen that the batteries will not achieve 100% of the SOC during the rainy season. In Figure 3-27, the probabilistic distribution of the cycles is shown in a histogram. During the whole year, each day, the batteries will achieve a SOC greater than 79%.

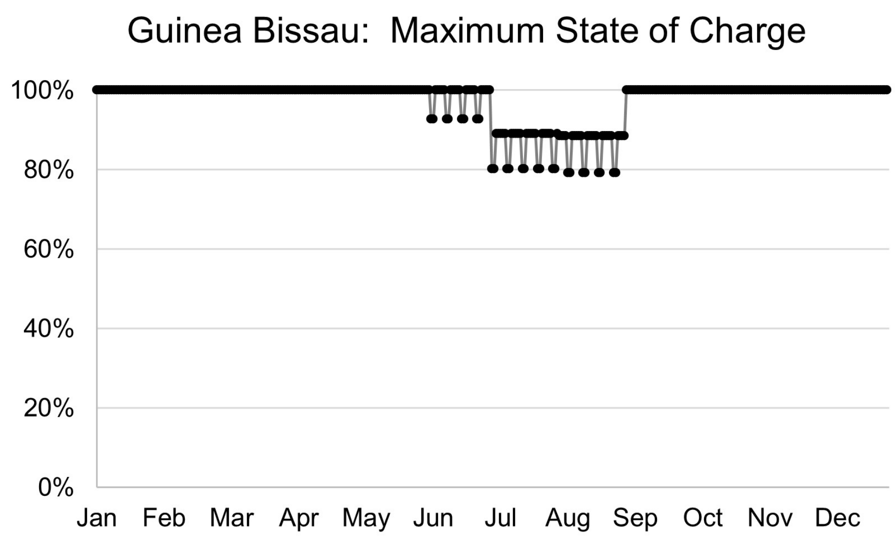


Figure 3-26: Guinea-Bissau - Daily Maximum SOC.

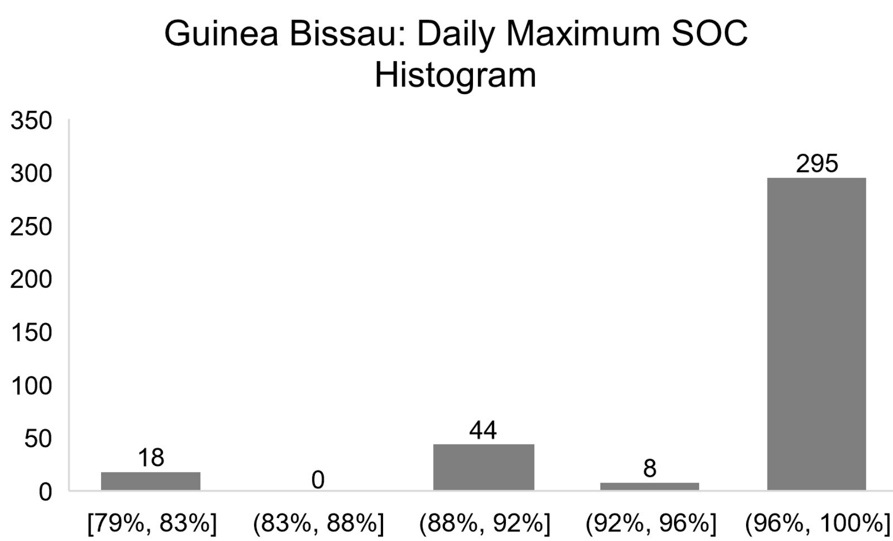


Figure 3-27: Guinea-Bissau - Daily Maximum SOC (Histogram).

Technology comparison

The same methodology used for subsection 3.3.2 is followed in this section for the selected case of Guinea-Bissau. Based on the number of effective cycles per year, average capacity efficiencies by year were calculated for ZEBRA batteries and LIBs. The results are shown in Table 3.4 with the capacity efficiencies for solar panels.

year	Solar	ZEBRA	LIBs
1	1	1	1
2	0.995	0.9832	0.9583
3	0.99	0.9664	0.9166
4	0.985	0.9496	0.8749
5	0.98	0.9328	0.8331
6	0.975	0.9161	0.7914
7	0.97	0.8993	1 (*new)
8	0.965	0.8825	0.9583
9	0.96	0.8657	0.9166
10	0.955	0.8489	0.8749
11	0.95	0.8321	0.8331
12	0.945	0.8153	0.7914

Table 3.4: Guinea-Bissau - Capacity efficiency table. (*) A replacement of all LIBs is considered in year 7.

The difference of energy delivered by the batteries is calculated. This exercise assumes that the energy difference will be bought from the grid in case it is negative. The value of energy considered is 0.58 USD/kWh (APANEWS, n.d.). Guinea-Bissau has one of the lowest electrification rates and highest costs of electric service in Africa. Currently, 90% of the electricity demand is covered with imported fuel and power imports from Senegal (*Guinea Bissau plans to cut electricity prices by 50% | The North Africa Post*, n.d.).

Figure 3-28 and Figure 3-29 show a comparison between both technologies for the selected case of Guinea-Bissau, an ESS of 288,000 kWh. The result is a positive NPV of 7.67 MUSD. The way the calculation is done, a positive number means that the preferred technology is ZEBRA. However, this value is relatively small in comparison to the initial investment of both technologies for this project. An initial investment of 172.8 MUSD is needed to deploy the project with ZEBRA Technology and 109.4

MUSD with LIBs.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Δ Capex [k USD]	(63,360)						109,440						
Δ Opex [k USD]		-	-	-	-	-	-	-	-	-	-	-	-
Δ Decommissioning cost [k USD]							10,944						(6,336)
Δ Energy supplied by bat. [GWh]		-	2	3	5	6	8	(6)	(5)	(3)	(2)	(0)	2
Δ Cost imported Energy [k USD]		-	890	1,814	2,741	3,760	4,792	(3,484)	(2,701)	(1,843)	(958)	(38)	918
Cash Flow [k USD]	(63,360)	-	890	1,814	2,741	3,760	125,176	(3,484)	(2,701)	(1,843)	(958)	(38)	(5,418)
Discounted Cash flow [k USD]	(63,360)	-	736	1,363	1,872	2,335	70,659	(1,788)	(1,260)	(781)	(369)	(13)	(1,726)
Cum. Disc. Cash flow [k USD]	(63,360)	(63,360)	(62,624)	(61,261)	(59,389)	(57,054)	13,605	11,817	10,557	9,775	9,406	9,392	7,666
NPV [k USD]	**7,666**												

Figure 3-28: Guinea-Bissau - Technology Comparison NPV.

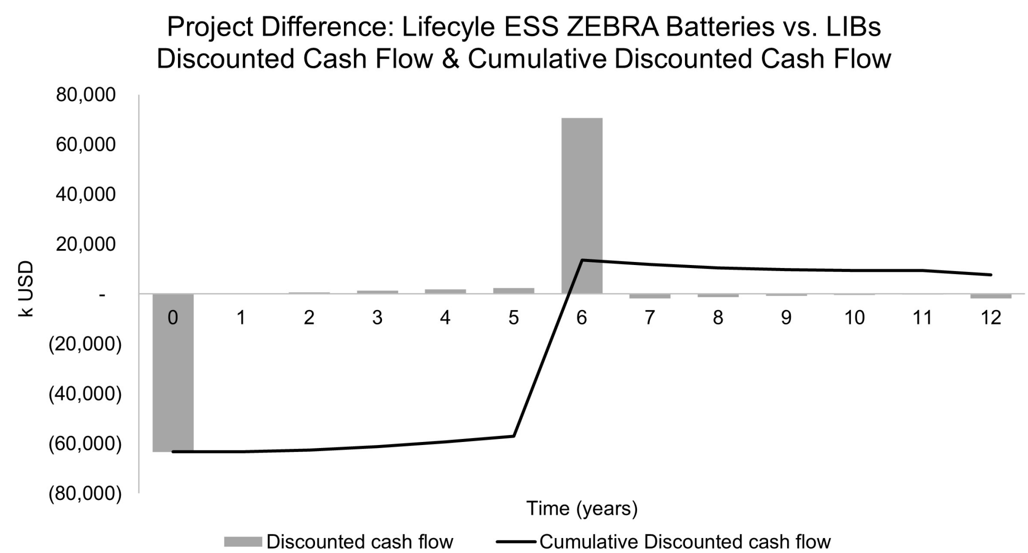


Figure 3-29: Guinea-Bissau - Technology Comparison Cash Flow.

Figure 3-30 shows a sensitivity analysis performed by changing the following variables related to the FOMs analyzed in section 2.4:

- ZEBRA Batteries Capital Cost 540 USD/kWh (-10% base case)
- ZEBRA Batteries Operation Cost 9 USD/kW-year (-10% base case)
- ZEBRA Batteries Degradation Rate = 0 (no degradation)
- ZEBRA Batteries Decommissioning Cost 9% of initial capital investment(-10% base case).

It is possible to see that the variable that impacts the most is the Cost of Capital. That is the reason why this variable was prioritized in section 2.9. Additionally, the degradation rate is essential in this analysis, as it relates to the high cost of alternative energy sources in the area.

The same model was tested with an IRR (discount rate) of 5%, and the result was an NPV of 28,505 kUSD.

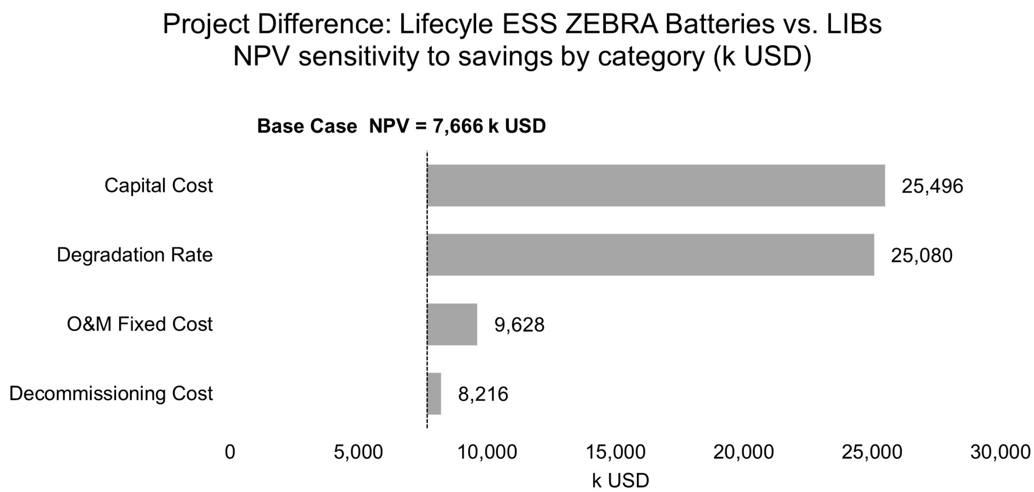


Figure 3-30: Guinea-Bissau - Technology Comparison NPV Sensitivity Analysis.

3.3.4 Texas selected case LCA

Annual characterization of charge/discharge cycles.

In Figure 3-21 it is possible to see the daily SOC for an entire year. The batteries will not have enough available VRE to achieve a SOC of 100% during the summer when the electricity demand is the highest in the year due to the use of air conditioner systems. In Figure 3-22, the probabilistic distribution of the cycles is shown in a histogram. From the cluster of cycles that belong to values below 20% of SOC, 67 of the 85 data points in the cluster have values equal to zero. That is to say that during a year, for this specific configuration, batteries will have 298 cycles, where 273 of them will have SOC greater than 80%.

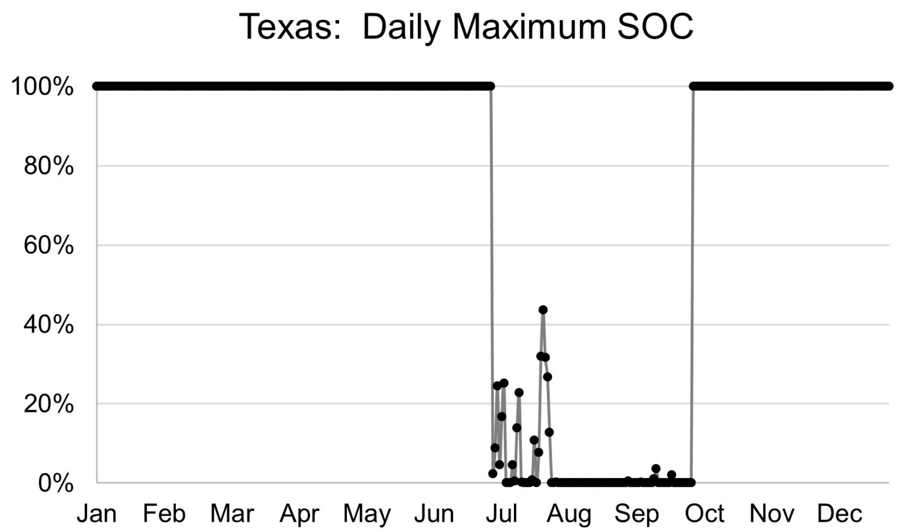


Figure 3-31: Texas - Daily Maximum SOC.

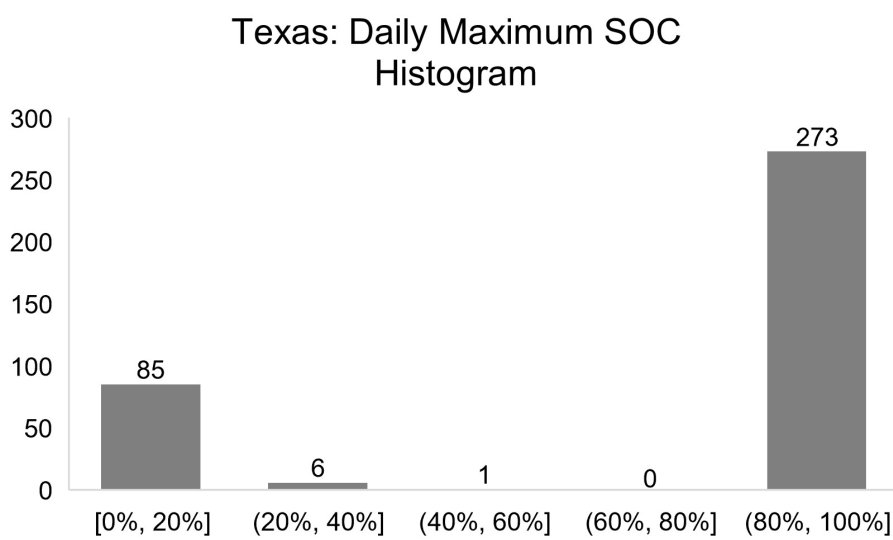


Figure 3-32: Texas - Daily Maximum SOC (Histogram).

Technology comparison

The same methodology used for subsection 3.3.2 is followed in this section for the selected case of Texas. Based on the number of effective cycles per year, average capacity efficiencies by year were calculated for ZEBRA batteries and LIBs. The results are shown in Table 3.5 with the capacity efficiencies for wind turbines and solar panels.

year	Wind Turbines	Solar	ZEBRA	LIBs
1	1	1	1	1
2	0.985	0.995	0.9863	0.9659
3	0.97	0.99	0.9726	0.9319
4	0.955	0.985	0.9589	0.8978
5	0.94	0.98	0.9452	0.8638
6	0.925	0.975	0.9315	0.8297
7	0.91	0.97	0.9178	1 (*new)
8	0.895	0.965	0.904	0.9659
9	0.88	0.96	0.8903	0.9319
10	0.865	0.955	0.8766	0.8978
11	0.85	0.95	0.8629	0.8638
12	0.835	0.945	0.8492	0.8297

Table 3.5: Texas - Capacity efficiency table. (*) A replacement of all LIBs is considered in year 7.

The difference of energy delivered by the batteries is calculated. This exercise assumes that the energy difference will be bought from the grid in case it is negative. The value of energy considered is 0.1215 USD/kWh (*Average Texas electricity prices were higher in February 2021 due to a severe winter storm - Today in Energy*, 2021).

Figure 3-33 and Figure 3-34 show a comparison of technologies for the selected case of Texas, an ESS of 96,000 MWh. The result is a positive NPV of 1,058 MUSD. The way the calculation is done, a positive number means that the preferred technology is ZEBRA. However, this value is small in comparison to the initial investment of both technologies for this project. An initial investment of 57,600 MUSD (about 60 Billion $) is needed to deploy the project with ZEBRA Technology and 36,480 MUSD with LIBs.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Δ Capex [MUSD]	(21,120)	-	-	-	-	-	36,480	-	-	-	-	-	-
Δ Opex [MUSD]	-	-	-	-	-	-	-	-	-	-	-	-	-
Δ Decommissioning cost [MUSD]													
Δ Energy supplied by bat. [GWh]		-	300	628	974	1,368	1,798	(1,405)	(1,108)	(782)	(410)	(17)	394
Δ Cost imported Energy [MUSD]	-	-	36	76	118	166	218	(171)	(135)	(95)	(50)	(2)	48
Cash Flow [MUSD]	(21,120)	-	36	76	118	166	36,698	(171)	(135)	(95)	(50)	(2)	48
Discounted Cash flow [MUSD]	(21,120)	-	30	57	81	103	22,775	(88)	(63)	(40)	(19)	(1)	(658)
Cum. Disc. Cash flow [MUSD]	(21,120)	(21,120)	(21,090)	(21,033)	(20,952)	(20,849)	1,926	1,838	1,776	1,735	1,716	1,715	1,058
NPV [MUSD]	**1,058**												

Figure 3-33: Texas - Technology Comparison NPV.

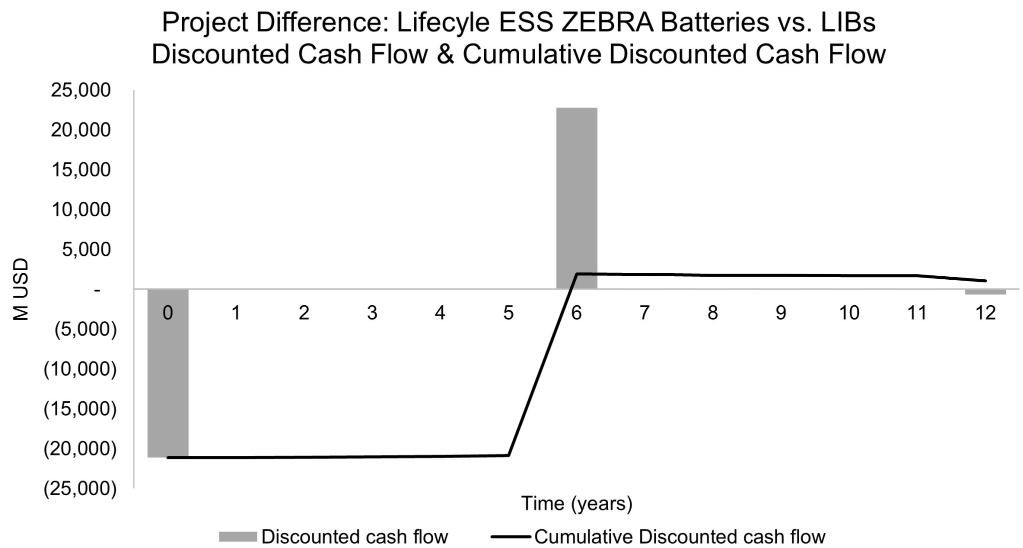


Figure 3-34: Texas - Technology Comparison Cash Flow.

Figure 3-35 shows a sensitivity analysis performed by changing the following variables related to the FOMs analyzed in section 2.4:

- ZEBRA Batteries Capital Cost 540 USD/kWh (-10% base case)
- ZEBRA Batteries Operation Cost 9 USD/kW-year (-10% base case)
- ZEBRA Batteries Degradation Rate = 0 (no degradation)
- ZEBRA Batteries Decommissioning Cost 9% of initial capital investment(-10% base case).

It is possible to see that the variable that impacts the most is the Cost of Capital. That is why this variable was prioritized in section 2.9.

The same model was tested with an IRR (discount rate) of 5%, and the result was an NPV of 7,859 MUSD.

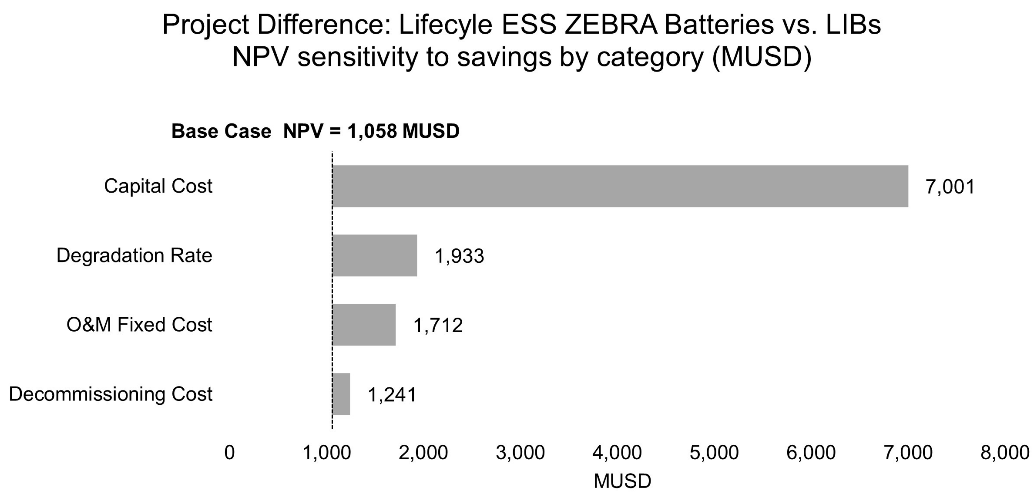


Figure 3-35: Texas - Technology Comparison NPV Sensitivity Analysis.

Chapter 4

Conclusions

4.1 First: Cost Reduction

This thesis considers that the most critical barrier to increasing the market share of ZEBRA Batteries is their cost, as it was shown in section 3.3, which is the same barrier for any battery technology nowadays.

The aim of Chapter 2 was to show a Technology Roadmap with R&T projects that will enable cost reduction of the ZEBRA Battery Technology. The most critical projects are related to the materials that compose a ZEBRA Battery.

A team specialized in Materials Science is needed in any ZEBRA manufacturer company that is willing to carry out R&T projects like the ones proposed in this study.

4.2 Trending topic: Decarbonization

As mentioned in Chapter 1, ESS will have a critical role in enabling deeper penetration of VRE in the electric market, as VRE demand will increase significantly in the upcoming years. Some countries will try to decarbonize their economy by expanding the participation of VRE. Another group of countries in the developing world is still trying to satisfy the increasing electricity demand with affordable and sustainable energy. The challenges are different, but customized ESS, like the ones designed in section 3.2, will help to overcome them.

As it may have been noted, a significant portion of the cited articles and references were very recent, which shows a real and increasing interest in this technology in different parts of the world.

4.3 Customized ESS solutions

The modeling section section 3.2 showed that hybrid energy systems have different optimal solutions depending on many conditions directly related to the location and climate where the renewable energy sources are located and the energy demand patterns of the consumers. The model provides a general structure to evaluate one year of performance of a hybrid energy system. It can be applied to different cases with different kinds of batteries and run for more than one year to capture the effects of the Annual RTE Degradation Factor. The model does not capture if surplus energy can be sold through any available electric grid. That would represent an extra income in the economic analysis.

In Chapter 3, many success cases were analyzed. It was possible to develop a stakeholder analysis and translate the stakeholders' needs into requirements for two different ZEBRA battery use cases. It was possible to see that the requirements for each use case may be very different as it is not the same to provide batteries for a wind farm in Maine or a remote village in Africa. People in Africa may need a cheaper battery, even if that means losing performance on the way. Increasing the content of iron (Fe) could be part of the solution. On the other hand, a wind farm may need excellent performance and very high capacity. The challenge for ZEBRA manufacturers is to be able to deploy projects of hundreds of MWh. Therefore, a new battery design should be considered.

4.4 ZEBRA battery as an invading technology

Even though ZEBRA technology is very well-known for telecommunications applications, the penetration of this technology in the market for ESS applications is very low compared to LIBs.

This study recognizes that the ZEBRA Battery performance in terms of safety and sustainability among other FOMs is better than the state-of-the-art LIBs. More marketing regarding these other FOMs should be done by ZEBRA batteries manufacturers to consumers. One of the limitations encountered to conduct this study has been the lack of quantitative information regarding how these new FOMs will translate into the NPV calculation of any project. For example, ZEBRA batteries are maintenance-free and do not need a cooling system (qualitative). How much is the impact of not requiring a cooling system on the O&M cost of a project? (quantitative). No quantitative information about the possible O&M cost reduction related to ZEBRA batteries in comparison to other technologies is available. The same value of 10 USD/kW-yr is used for any ESS project analyzed in a study performed in 2019 (Mongird et al., 2019). The sensitivity analysis performed in section 3.3 tried to capture the impact of a possible reduction of O&M costs.

Because of its characteristics, this technology can outperform LIBs in stationary applications in high-temperature environments, as its maximum temperature of operation is +60°C (and being able to work under peaks of +75°C) with no cooling system needed. This could be a relative advantage in locations like Texas or Guinea-Bissau. That would be a very interesting FOM to advertise. Additionally, quantitative information should be given to ZEBRA technology potential buyers regarding the degradation rate of LIBs in high-temperature environments for peak-shaving operations, as many recent studies have shown.

4.5 Possible threats to ZEBRA technology

4.5.1 New battery technologies

New chemical formulas for batteries are being studied to help overcome the challenge of a deeper penetration of renewable energy in the electrical market. Some of them were initially thought to be cheap intrinsically. One example could be the technology developed by Professor Donald Sadoway from Massachusetts Institute of Technology (MIT) at his company "Ambri." Concerning the need to provide a low-cost battery from its ideation, Professor Sadoway states that "If you want something to be cheap as dirt, make it out of dirt" (Sadower & Shao-Horn, n.d.).

Most of these battery technologies do not have the Technology Readiness Level (TRL) and the Manufacturing Readiness Level (MRL) that ZEBRA batteries currently have. According to (Mongird et al., 2019), ZEBRA batteries have a TRL of 6 and a MRL of 7, which is a competitive advantage that this technology has nowadays. However, as new technologies develop fast, this advantage can disappear in the next five to ten years. It is undesirable to rely on old technology without incorporating improvements and adapting them quickly for each use case. Battery customization is needed to increase ZEBRA Batteries' market share and establish a more robust position before invading battery technologies are potentially commercialized in a few years.

4.5.2 The issue of Nickel

The future of this technology will depend on how the different ZEBRA manufacturers will address the rising demand for Nickel. This study mentions a set of options that can be executed in parallel to solving this issue:

- Reduce the content of Nickel and increase the proportion of iron.
- Recycle old ZEBRA batteries so the Nickel can be reused.
- Look for alternative mining processes for Nickel, such as extracting Nickel from seawater.

- Look for an alliance with a Nickel supplier or mining company.

4.6 Other opportunities to reduce capital cost

Other projects to reduce the cost of the ZEBRA batteries were not developed in-depth in this thesis and would be of interest for future studies, for example:

- The impact of economies of scale.
- Lean Operations opportunities to reduce assembly costs.
- Labor Arbitrage, opening a new factory with cheaper labor force than the one in Switzerland (closer to the market, African and Asian Markets), but ensuring decent job conditions: fair payment, healthy environment, no child labor.
- Location of Factory - Market - Recycling plant: These three must be close to each other geographically (cluster) for CO_2 and cost reduction purposes.

Appendix A

Tables

Table A.1: List of Energy Storage Projects worldwide. Source: *Global Energy Storage Projects Database* (2020)

Project Name	**Power (kW)**	**Duration (h)**	**Energy (kWh)**	**Country**
Rankin Substation Energy Storage Project	402	0.7	281.4	United States
INES Project	120	1.17	140.4	France
Xcel SolarTAC CES Test	25	2	50	United States
EDF EN Gabardone Project	20	3.5	70	France
Gasfinolhu Island Resort	600	2.5	1500	Maldives
SMUD Solar EV Charge Port	50	2.6	130	United States
GE Tehachapi Wind Durathon Battery Project - Invenergy	300	4	1200	United States
29 Palms Durathon Battery Project	500	2	1000	United States

Continued on next page

Table A.1 – *Continued from previous page*

Project Name	**Power (kW)**	**Duration (h)**	**Energy (kWh)**	**Country**
Goldthwaite Storage-Invenergy	600	2	1200	United States
Annobon Island Microgrid	5000	2	10000	Equatorial Guinea
Smart Polygeneration Microgrid, Univeristy of Genoa	63	2.37	149.31	Italy
Terna Storage Lab 2, Sicily (5)	1200	3.45	4140	Italy
EDF EN Guiana, Toucan Project	1600	2.8	4480	French Guiana
TILOS	800	3	2400	Greece
ALTAIS	120	1.67	200.4	Martinique
Wind Energy Institute of Canada	1000	2	2000	Canada
Terna Storage Lab 1, Sardinia (6)	1200	3.45	4140	Italy
Terna Storage Lab 1, Sardinia (7)	1000	2	2000	Italy
FIAMM Green Energy Island	180	1.27	228.6	Italy
Terna Grid Defense Plan Phase II (2)	4000	0	0	Italy

Continued on next page

Table A.1 – *Continued from previous page*

Project Name	**Power (kW)**	**Duration (h)**	**Energy (kWh)**	**Country**
Management Demonstration for USAF High Energy Demand Operations and Facilities	100	2	200	United States
Arista Durathon Battery Project	100	2	200	United States
WPD Falcon Project, GE Durathon	250	2	500	United Kingdom
Enel Livorno Test Facility: 20 kW ZEBRA	20	1	20	Italy
POSCO Secondary Battery Research Activity	198	0.7	138.6	South Korea
State Grid Shanghai FI-AMM Battery Project	100	1.7	170	China
Tozzi Energy Storage System - TESS	35	3	105	Italy
Discovery Science Center Durathon Battery	100	5	500	United States

Table A.2: Eastport, Maine. Total photovoltaic power output [kWh] for 1000 kWp Installed capacity. Source: *Global Solar Atlas* (n.d.)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0-1	0	0	0	0	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0	0	0	0	0	0
4-5	0	0	0	0	0.1	0.3	0	0	0	0	0	0
5-6	0	0	0	1.5	11.8	17.3	11.1	2.4	0.1	0	0	0
6-7	0	0	3.4	30.1	53.3	57.2	46.5	32.7	15.7	1.4	0	0
7-8	0.1	9.9	80	132.7	157.4	153.4	135.7	132.6	122	77.9	8.1	0.1
8-9	42.9	146.9	238.8	271.9	284.4	278.1	263.7	273.2	272.6	232.5	106.4	36.7
9-10	186.8	326.1	380.1	397.5	400.5	391.3	383.2	405.6	410.6	352.8	263.1	148.9
10-11	356.8	435.9	484.4	482.1	479.9	480	486.1	505.8	499.4	433.6	338	292.3
11-12	426.3	503.2	549	541.6	531.9	528.9	546.2	565.9	560.1	479.7	384.6	366.7
12-13	461.8	533.3	576.1	564.3	559.2	553.1	581.6	591.5	581.3	483.9	391	382.5
13-14	440.1	512.5	554.4	553.1	535.1	531.7	559.2	568.4	555.3	448.4	356.5	356.7
14-15	376.6	446.4	487.3	481.5	476.3	471.6	501.8	503.5	480.2	372.6	290.6	252.2
15-16	233.3	348.4	378.7	379.3	390.9	391.4	415.9	411.4	371.1	271.6	164.2	119.3
16-17	69.3	215.1	264.2	264.9	273.7	278.5	300.1	290.5	239.8	143.3	34.7	18.8
17-18	1.5	38.2	113.9	128.3	143.4	155.1	166.6	149.1	91.8	14.7	0.1	0
18-19	0	0.1	9.6	27.6	45.6	55.7	60	39.4	7.5	0	0	0
19-20	0	0	0	0.8	8.5	16.6	15.7	3.8	0	0	0	0
20-21	0	0	0	0	0	0.2	0.2	0	0	0	0	0
21-22	0	0	0	0	0	0	0	0	0	0	0	0
22-23	0	0	0	0	0	0	0	0	0	0	0	0
23-24	0	0	0	0	0	0	0	0	0	0	0	0

Table A.3: Eastport, Maine. Wind velocity [m/s] at 100 m. Source: *Global Wind Atlas* (n.d.)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0-1	9.31	8.46	10.49	8.97	8.71	8.71	8.54	8.29	8.46	8.63	8.97	9.81
1-2	9.39	8.63	10.49	9.05	8.8	8.54	8.63	8.29	8.54	8.54	9.05	10.07
2-3	9.48	8.63	10.41	9.05	8.71	8.46	8.63	8.29	8.46	8.46	8.97	9.98
3-4	9.56	8.63	10.32	8.97	8.63	8.46	8.54	8.04	8.29	8.63	8.88	9.9
4-5	9.64	8.63	10.15	8.97	8.63	8.29	8.21	7.78	8.12	8.71	9.05	9.81
5-6	9.64	8.8	9.9	8.8	8.46	8.04	8.04	7.44	8.04	8.71	9.14	9.64
6-7	9.56	8.88	9.81	8.8	8.29	7.7	7.78	7.11	7.87	8.71	8.97	9.56
7-8	9.39	8.8	9.98	8.63	8.21	7.44	7.53	7.02	7.7	8.8	8.8	9.64
8-9	9.39	8.63	9.98	8.54	8.21	7.36	7.36	7.02	7.53	8.8	8.88	9.81
9-10	9.39	8.38	9.9	8.63	8.21	7.44	7.36	7.02	7.36	8.8	8.88	9.81
10-11	9.31	8.12	9.73	8.63	8.29	7.44	7.28	6.85	7.28	8.71	8.88	9.81
11-12	9.22	8.12	9.64	8.63	8.29	7.19	6.85	6.6	7.28	8.54	9.05	9.81
12-13	9.05	8.21	9.56	8.46	7.87	6.68	6.18	6.01	7.11	8.21	9.05	9.73
13-14	8.71	8.21	9.39	8.12	7.36	6.43	5.75	5.58	6.68	7.87	9.05	9.64
14-15	8.38	8.38	8.97	7.95	7.19	6.51	5.75	5.5	6.51	7.61	9.05	9.64
15-16	8.21	8.38	8.63	8.04	7.28	6.85	6.09	5.75	6.35	7.61	9.14	9.73
16-17	7.87	8.21	8.71	8.38	7.61	7.36	6.6	6.26	6.35	7.61	9.14	9.73
17-18	7.95	8.12	8.88	8.8	8.04	7.78	7.02	6.77	6.6	7.53	9.22	9.56
18-19	8.04	8.46	8.88	9.31	8.29	8.38	7.44	7.36	6.85	7.53	9.31	9.48
19-20	8.21	8.8	9.05	9.56	8.38	8.97	7.87	7.7	7.02	7.7	9.22	9.39
20-21	8.21	9.22	9.48	9.64	8.63	9.31	8.46	8.04	7.28	7.78	9.14	9.31
21-22	8.38	9.31	9.81	9.56	8.63	9.39	8.8	8.21	7.61	7.87	9.05	9.31
22-23	8.63	9.56	9.81	9.39	8.71	9.31	8.97	8.29	7.95	8.04	8.97	9.31
23-24	8.8	9.9	9.81	9.22	8.8	9.14	8.88	8.29	8.38	8.21	8.97	9.48

Table A.4: Bafatá, Guinea Bissau. Total photovoltaic power output [kWh] for 1000 kWp Installed capacity. Source: *Global Solar Atlas* (n.d.)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0-1	0	0	0	0	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0	0	0	0	0	0
5-6	0	0	0	0	0.4	0.6	0.2	0	0	0	0	0
6-7	2.7	5.8	23.1	41.9	62.3	53.8	47.5	38.2	44	42.1	40	16.1
7-8	148.6	146.4	179.1	216.4	205.7	170.8	161	160.5	183.8	209.3	228.1	187.8
8-9	360.8	352.3	369.9	397.5	361.3	297.4	281.8	276.9	318.1	368	404.9	381.4
9-10	525.2	526.9	537.5	547.9	497.2	414.4	384.9	389.1	456	513.3	550.3	534.2
10-11	644.3	656.2	662	658.3	593.2	498.6	470.7	484.3	560	623.5	648.8	639.1
11-12	705	722.8	725.9	707.3	639.9	547.6	514.1	525.1	595.4	658.2	685.2	686.7
12-13	704.1	726.8	721.1	701.7	629.1	556.2	520.1	515.5	585.9	643.5	664.5	674.3
13-14	642.5	670.1	663.1	638.7	570.2	513	488	468.3	525	578.2	589.4	604.5
14-15	539.3	566.2	557.8	528.3	467.9	421.3	402.4	394.3	436.4	463	468.9	489.6
15-16	386.9	416	403.6	376.3	329.7	303.9	293.6	286.7	299.6	304.6	305.2	333.8
16-17	200.5	230.1	218.9	200	175.5	167.5	165.5	157.5	147	120.5	116.8	141.2
17-18	21.8	40.5	39.6	42.2	39.5	48.7	53.3	41.6	23.9	4.2	3	4.8
18-19	0	0	0	0	0	0.5	1.8	0	0	0	0	0
19-20	0	0	0	0	0	0	0	0	0	0	0	0
20-21	0	0	0	0	0	0	0	0	0	0	0	0
21-22	0	0	0	0	0	0	0	0	0	0	0	0
22-23	0	0	0	0	0	0	0	0	0	0	0	0
23-24	0	0	0	0	0	0	0	0	0	0	0	0

Table A.5: Texas, USA. Wind velocity [m/s] at 100 m. Source: *Global Wind Atlas* (n.d.)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0-1	8.8	8.72	9.23	9.66	9.06	9.23	7.35	6.84	7.01	8.46	8.89	9.4
1-2	9.34	9.25	9.79	10.25	9.61	9.79	7.8	7.26	7.44	8.98	9.43	9.98
2-3	9.88	9.78	10.36	10.84	10.17	10.36	8.25	7.67	7.87	9.5	9.98	10.55
3-4	10.24	10.14	10.74	11.23	10.54	10.74	8.55	7.95	8.15	9.84	10.34	10.93
4-5	10.42	10.32	10.92	11.43	10.72	10.92	8.7	8.09	8.29	10.01	10.52	11.13
5-6	10.42	10.32	10.92	11.43	10.72	10.92	8.7	8.09	8.29	10.01	10.52	11.13
6-7	10.33	10.23	10.83	11.33	10.63	10.83	8.62	8.02	8.22	9.93	10.43	11.03
7-8	10.24	10.14	10.74	11.23	10.54	10.74	8.55	7.95	8.15	9.84	10.34	10.93
8-9	10.15	10.05	10.64	11.13	10.44	10.64	8.47	7.88	8.08	9.76	10.25	10.84
9-10	10.06	9.96	10.55	11.04	10.35	10.55	8.4	7.81	8.01	9.67	10.16	10.74
10-11	9.97	9.87	10.45	10.94	10.26	10.45	8.32	7.74	7.94	9.58	10.07	10.65
11-12	9.88	9.78	10.36	10.84	10.17	10.36	8.25	7.67	7.87	9.5	9.98	10.55
12-13	9.79	9.69	10.27	10.74	10.08	10.27	8.17	7.6	7.79	9.41	9.88	10.46
13-14	9.61	9.52	10.08	10.54	9.89	10.08	8.02	7.46	7.65	9.24	9.7	10.26
14-15	8.98	8.89	9.42	9.85	9.24	9.42	7.5	6.98	7.15	8.63	9.07	9.59
15-16	8.44	8.36	8.85	9.26	8.69	8.85	7.05	6.56	6.72	8.11	8.52	9.02
16-17	7.81	7.74	8.19	8.57	8.04	8.19	6.52	6.07	6.22	7.51	7.89	8.35
17-18	7.36	7.29	7.72	8.08	7.58	7.72	6.15	5.72	5.86	7.08	7.44	7.87
18-19	7.1	7.03	7.44	7.78	7.3	7.44	5.92	5.51	5.65	6.82	7.16	7.58
19-20	7.01	6.94	7.35	7.69	7.21	7.35	5.85	5.44	5.58	6.73	7.07	7.48
20-21	7.1	7.03	7.44	7.78	7.3	7.44	5.92	5.51	5.65	6.82	7.16	7.58
21-22	7.28	7.2	7.63	7.98	7.49	7.63	6.07	5.65	5.79	6.99	7.35	7.77
22-23	7.45	7.38	7.82	8.18	7.67	7.82	6.22	5.79	5.93	7.17	7.53	7.96
23-24	7.72	7.65	8.1	8.47	7.95	8.1	6.45	6	6.15	7.42	7.8	8.25

Table A.6: Texas. Total photovoltaic power output [kWh] for 1000 kWp Installed capacity. Source: *Global Solar Atlas* (n.d.)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0-1	0	0	0	0	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0	0	0	0	0	0
4-5	0	0	0	0	1.4	3.1	0.9	0	0	0	0	0
5-6	0	0	1.8	18.4	37.4	40.7	31.9	20	11.3	2.9	0	0
6-7	5.3	24.8	72.6	122.7	140.7	144.8	134.5	128.9	124.4	109.5	50.8	10.3
7-8	157	179.8	227.3	273.3	273.1	289.4	291.8	297.8	291.9	273.8	237.7	170.5
8-9	344.5	341.8	380.1	415.5	399.2	420.8	435.1	453.8	442.7	412.5	385.4	346.5
9-10	474.9	475.6	506	533.5	501.9	535.6	548.6	573.6	556.5	522.8	496.5	466.6
10-11	558.6	565.3	589.8	609	571.6	599.5	618.8	640.2	621.1	594	559.5	536.3
11-12	585.3	605.7	623	642.2	598	624.5	639.3	657.7	631.2	611.1	572.6	557.9
12-13	572.8	597.4	613.1	627.7	599	621	623.2	630.5	604.5	588.9	554.6	541.4
13-14	523	552.4	562.6	573.6	541.9	563.8	565.6	568.4	536.9	520.4	488	480
14-15	420.7	453.4	462	465.5	437.1	462.8	463.5	460.4	427.7	405.5	366	370.2
15-16	270.2	308.7	322.4	319.4	301.9	326.1	330.5	321.5	283.2	240.4	197.4	196.6
16-17	53.3	128.4	153.4	153.6	151.3	170.4	178.1	163.5	118	61.7	16.2	14
17-18	0.1	4	19	30.1	40.8	52.2	54.5	40.1	11	0.3	0	0
18-19	0	0	0	0.2	2.1	7.1	6.7	1.3	0	0	0	0
19-20	0	0	0	0	0	0	0	0	0	0	0	0
20-21	0	0	0	0	0	0	0	0	0	0	0	0
21-22	0	0	0	0	0	0	0	0	0	0	0	0
22-23	0	0	0	0	0	0	0	0	0	0	0	0
23-24	0	0	0	0	0	0	0	0	0	0	0	0

Appendix B

Figures

OPL spec.
Energy Storage Systems is physical and systemic.
Batteries is physical and systemic.
Molten Salt Batteries is physical and systemic.
Sodium–sulfur Batteries is physical and systemic.
Zebra Batteries is physical and systemic.
Lead Acid Batteries is physical and systemic.
Lithium-ion Batteries is physical and systemic.
Batteries is a **Energy Storage Systems**.
Lead Acid Batteries, **Lithium-ion Batteries** and **Molten Salt Batteries** are **Batteries**.
Sodium–sulfur Batteries and **Zebra Batteries** are **Molten Salt Batteries**.

Figure B-1: Energy Storage Family for ZEBRA Battery OPL.

OPL spec.
Energy Consumers is physical and systemic.
Energy Demand of Energy Consumers is informatical and systemic.
Environmentaly, Sustainably of Supplying is informatical and systemic.
Electricity Consumers is physical and systemic.
Energy Demand of Electricity Consumers is informatical and systemic.
Safely, Efficiently, Low Maintenance of Storing is informatical and systemic.
Energy Storage Systems is physical and systemic.
Batteries is physical and systemic.
Zebra Technology of Batteries is informatical and systemic.
Electricity Consumers exhibits Energy Demand.
Storing is Supplying.
Supplying exhibits Environmentaly, Sustainably.
Storing exhibits Safely, Efficiently, Low Maintenance.
Batteries is a Energy Storage Systems.
Batteries exhibits Zebra Technology.
Energy Consumers exhibits Energy Demand.
Electricity Consumers is a Energy Consumers.
Supplying is physical and systemic.
Supplying affects Energy Demand of Energy Consumers.
Storing is physical and systemic.
Storing requires Energy Storage Systems.
Storing affects Energy Demand of Electricity Consumers.

Figure B-2: SPS for ZEBRA batteries using the To-By-Using framework acrshortOPL.

SD

Zebra Battery is physical and systemic.
Cells is physical and systemic.
Insulation is physical and systemic.
Case is physical and systemic.
Battery Management System is physical and systemic.
Energy Density of Zebra Battery is informatical and systemic.
Power Density of Zebra Battery is informatical and systemic.
Cycle Life of Zebra Battery is informatical and systemic.
Functional Performance Metrics is informatical and systemic.
Round Trip Efficiency of Zebra Battery is informatical and systemic.
Annual RTE Degradation Factor of Zebra Battery is informatical and systemic.
Durathon E620 is physical and systemic.
Fzsonick 48TL200 is physical and systemic.
LCOS of Zebra Battery is informatical and systemic.
Electrical Energy is physical and systemic.
Other FOM's is informatical and systemic.
Figures of Merit is informatical and systemic.
Recycling Efficiency of Zebra Battery is informatical and systemic.
Cost Of Capital of Zebra Battery is informatical and systemic.
Maintenance of Zebra Battery is informatical and systemic.
Carbon Footprint of Zebra Battery is informatical and systemic.
Zebra Battery consists of Battery Management System, Case, Cells and Insulation.
Annual RTE Degradation Factor, Cycle Life, Energy Density, Power Density and Round Trip Efficiency are Functional Performance Metrics.
Zebra Battery exhibits Annual RTE Degradation Factor, Carbon Footprint, Cost Of Capital, Cycle Life, Energy Density, LCOS, Maintenance, Power Density, Recycling Efficiency and Round Trip Efficiency.
Durathon E620 and Fzsonick 48TL200 are instances of Zebra Battery.
Functional Performance Metrics and Other FOM's are Figures of Merits.
Carbon Footprint, Cost Of Capital, LCOS, Maintenance and Recycling Efficiency are Other FOM's.
Storing is physical and systemic.
Storing requires Zebra Battery.
Storing affects Electrical Energy.

Figure B-3: System-level diagram (SD) for ZEBRA Battery OPL.

Storing

Storing from SD zooms in SD1 into Charging, and Discharging, which occur in that time sequence.
Electrical Energy is physical and systemic.
Zebra Battery is physical and systemic.
State of Cells is informatical and systemic.
State of Cells can be discharged or charged.
Chemical Energy is physical and systemic.
Losses is physical and systemic.
Cells is physical and systemic.
Insulation is physical and systemic.
Case is physical and systemic.
Battery Management System is physical and systemic.
Zebra Battery consists of Battery Management System, Case, Cells and Insulation.
Cells exhibits State.
Controling relates to Storing.
Storing is physical and systemic.
Storing requires Zebra Battery.
Storing affects Electrical Energy.
Insulating is physical and systemic.
Insulating requires Insulation.
Insulating affects Cells.
Covering is physical and systemic.
Covering requires Case.
Covering affects Cells and Insulation.
Controling is physical and systemic.
Controling requires Battery Management System.
Charging is physical and systemic.
Charging changes State of Cells from discharged to charged.
Charging consumes Electrical Energy.
Charging yields Chemical Energy and Losses.
Discharging is physical and systemic.
Discharging changes State of Cells from charged to discharged.
Discharging consumes Chemical Energy.
Discharging yields Electrical Energy and Losses.

Figure B-4: Subsystem level diagram (SD1.1) for Storing OPL.

Cells
Cells is physical and systemic.
Zebra Battery is physical and systemic.
State of Cells is informatical and systemic.
State of Cells can be charged or discharged.
Negative Electrode is physical and systemic.
Positive Electrode is physical and systemic.
Solid Electrolyte is physical and systemic.
Liquid Electrolyte is physical and systemic.
Cell Case is physical and systemic.
Current Collector is physical and systemic.
Zebra Battery consists of Cells and three more parts.
Cells exhibits State.
Cells consists of Cell Case, Current Collector, Liquid Electrolyte, Negative Electrode, Positive Electrode and Solid Electrolyte.
Insulating is physical and systemic.
Insulating affects Cells.
Covering is physical and systemic.
Covering affects Cells.
Separating is physical and systemic.
Separating requires Solid Electrolyte.
Separating affects Negative Electrode and Positive Electrode.

Figure B-5: Subsystem level diagram (SD1.2) for ZEBRA Battery Cells OPL.

Battery Management System (BMS)
Battery Management System is physical and systemic.
Measurement Block is physical and systemic.
Battery Algorithm Block is physical and systemic.
Capability Estimation Block is physical and systemic.
Zebra Battery is physical and systemic.
Cell Equalization Lock is physical and systemic.
Thermal Management Block is physical and systemic.
Battery Management System consists of Battery Algorithm Block, Capability Estimation Block, Cell Equalization Lock, Measurement Block and Thermal Management Block.
Zebra Battery consists of Battery Management System and three more parts.
Controling is physical and systemic.
Controling requires Battery Management System.

Figure B-6: Subsystem level diagram (SD1.3) for Battery Management System OPL.

SD

Zebra Battery is physical and systemic.
Energy is physical and systemic.
Nacl is physical and systemic.
B-alumina is physical and systemic.
Steel is physical and systemic.
Ni + Fe + Al is physical and systemic.
Materials is physical and systemic.
Safe of **Reclycing** is informatical and systemic.
Environment Friendly of **Reclycing** is informatical and systemic.
Efficient of **Reclycing** is informatical and systemic.
Plastic is physical and systemic.
Clay Substitute is physical and systemic.
Electronic Waste is physical and systemic.
Copper is physical and systemic.
B-alumina, **Copper**, **Nacl**, **Ni + Fe + Al**, **Plastic** and **Steel** are **Materials**.
Reclycing exhibits **Efficient**, **Environment Friendly** and **Safe**.
Manufacturing is physical and systemic.
Manufacturing consumes **Energy** and **Materials**.
Manufacturing yields **Zebra Battery**.
Reclycing is physical and systemic.
Reclycing consumes **Energy** and **Zebra Battery**.
Reclycing yields **Clay Substitute**, **Copper**, **Electronic Waste**, **Ni + Fe + Al**, **Plastic** and **Steel**.

Figure B-7: System-level diagram (SD) for ZEBRA Batteries Recycling and Manufacturing Processes OPL.

Reclycing

Reclycing from SD zooms in SD1 into Disassembling-2, Disassembling-1, Processing, Melting, and Disassembling-3, which occur in that time sequence.
Zebra Battery is physical and systemic.
Energy is physical and systemic.
Steel is physical and systemic.
Ni + Fe + Al is physical and systemic.
Safe of Reclycing is informatical and systemic.
Environment Friendly of Reclycing is informatical and systemic.
Efficient of Reclycing is informatical and systemic.
Plastic is physical and systemic.
Clay Substitute is physical and systemic.
Electronic Waste is physical and systemic.
Case is physical and systemic.
Cells is physical and systemic.
Insulation is physical and systemic.
Battery Management System is physical and systemic.
Ceramic is physical and systemic.
Nacl is physical and systemic.
Cells Case is physical and systemic.
Copper is physical and systemic.
Reclycing exhibits Efficient, Environment Friendly and Safe.
Zebra Battery consists of Battery Management System, Case, Cells and Insulation.
Reclycing is physical and systemic.
Reclycing consumes Energy.
Disassembling-1 is physical and systemic.
Disassembling-1 consumes Zebra Battery.
Disassembling-1 yields Battery Management System, Case, Cells and Insulation.
Disassembling-3 is physical and systemic.
Disassembling-3 consumes Battery Management System.
Disassembling-3 yields Electronic Waste and Plastic.
Melting is physical and systemic.
Melting consumes Case and Cells Case.
Melting yields Steel.
Processing is physical and systemic.
Processing consumes Ceramic and Nacl.
Processing yields Clay Substitute.
Disassembling-2 is physical and systemic.
Disassembling-2 consumes Cells.
Disassembling-2 yields Cells Case, Ceramic, Copper, Nacl and Ni + Fe + Al.

Figure B-8: Subsystem level diagram (SD1) for Recycling OPL.

SD

Electrical Energy is physical and systemic.

Electric Grid is physical and systemic.

Wind Energy is physical and environmental.

Solar Energy is physical and environmental.

Wind Turbines is physical and systemic.

Solar Panels is physical and systemic.

Location of Electrical Energy is informatical and systemic.

Location of Electrical Energy can be production or demand.

Renewable Energy is physical and environmental.

Battery is physical and systemic.

Chemical Energy is physical and systemic.

Work is physical and systemic.

Demand is physical and systemic.

Domestic Demand is physical and systemic.

Industrial Demand is physical and systemic.

Losses is physical and systemic.

Losses is physical and systemic.

C-rate of Battery is informatical and systemic.

Electrical Energy exhibits Location.

Solar Energy and Wind Energy are Renewable Energies.

Storing consists of Charging and Discharging.

Domestic Demand and Industrial Demand are Demands.

Battery exhibits C-rate.

Transporting is physical and systemic.

Transporting changes Location of Electrical Energy from production to demand.

Transporting requires Electric Grid.

Transforming is physical and systemic.

Transforming requires Wind Turbines.

Transforming consumes Wind Energy.

Transforming yields Electrical Energy.

Transforming is physical and systemic.

Transforming requires Solar Panels.

Transforming consumes Solar Energy.

Transforming yields Electrical Energy.

Storing is physical and systemic.

Storing requires Battery.

Charging is physical and systemic.

Charging consumes Electrical Energy.

Charging yields Chemical Energy and Losses.

Discharging is physical and systemic.

Discharging consumes Chemical Energy.

Discharging yields Electrical Energy and Losses.

Consuming is physical and systemic.

Consuming requires Demand.

Consuming consumes Electrical Energy.

Consuming yields Losses and Work.

Figure B-9: Representation of Supply-Demand System for Utility Applications OPL.

SD
Electrical Energy is physical and systemic.
Electric Grid is physical and systemic.
Wind Energy is physical and environmental.
Solar Energy is physical and environmental.
Wind Turbines is physical and systemic.
Solar Panels is physical and systemic.
Location of Electrical Energy is informatical and systemic.
Location of Electrical Energy can be production or demand.
Renewable Energy is physical and environmental.
Battery is physical and systemic.
Chemical Energy is physical and systemic.
Work is physical and systemic.
Demand is physical and systemic.
Domestic Demand is physical and systemic.
Industrial Demand is physical and systemic.
Losses is physical and systemic.
Losses is physical and systemic.
C-rate of Battery is informatical and systemic.
Electrical Energy exhibits Location.
Solar Energy and Wind Energy are Renewable Energies.
Storing consists of Charging and Discharging.
Domestic Demand and Industrial Demand are Demands.
Battery exhibits C-rate.
Transporting is physical and systemic.
Transporting changes Location of Electrical Energy from production to demand.
Transporting requires Electric Grid.
Transforming is physical and systemic.
Transforming requires Wind Turbines.
Transforming consumes Wind Energy.
Transforming yields Electrical Energy.
Transforming is physical and systemic.
Transforming requires Solar Panels.
Transforming consumes Solar Energy.
Transforming yields Electrical Energy.
Storing is physical and systemic.
Storing requires Battery.
Charging is physical and systemic.
Charging consumes Electrical Energy.
Charging yields Chemical Energy and Losses.
Discharging is physical and systemic.
Discharging consumes Chemical Energy.
Discharging yields Electrical Energy and Losses.
Consuming is physical and systemic.
Consuming requires Demand.
Consuming consumes Electrical Energy.
Consuming yields Losses and Work.

Figure B-10: Representation of Supply-Demand System for Domestic Applications OPL.

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