Sea Salt Battery serving as a Battery Technology in Electric Rickshaws in New Delhi, India: A Feasibility Study

Author

L. J. R. N. van Mameren

First supervisor

Dr. L. M. Kamp

Second supervisor

Dr. J. O. Kroesen

Master of Science

Sustainable Energy Technology

Faculty

Electrical Engineering, Mathematics and Computer Science

TU Delft

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EXECUTIVE SUMMARY

Lead-acid and lithium-ion batteries used for electric-rickshaw in India fail far short of their expected battery lifespan. Also, the materials being used have unfavorable consequences for the environment. A new type of battery made from sea salt has recently been invented. The sea salt battery could potentially be a better, cheaper, and greener battery. This thesis aimed to explore the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India, in order to answer the following main research question: *How can the sea salt battery become a feasible technology for electric rickshaws in New Delhi, India?* The answering of the main question of this thesis was divided into three sub-questions:

1. *How can the sea salt battery become technically feasible for electric rickshaws?*
2. *How can the sea salt battery become economically feasible for electric rickshaws?*
3. *How can the sea salt battery become socially feasible for electric rickshaws?*

Both qualitative and quantitative methods were applied within this exploratory research. In order to collect data for answering the sub-questions, data collection methods were applied. A desk study was conducted in order to collect the data serving as input for data analysis. Semi-structured interviews with several stakeholders were conducted in order to collect and verify data serving as input for data analysis. Semi-structured interviews were conducted among the stakeholders involved in the e-rickshaw sector. Online interviews were conducted with several entrepreneurs who largely operate in New Delhi.

To analyze the data, in order to answer the sub-questions, a feasibility analysis was used. The feasibility analysis started with reviewing the summarized interviews. Furthermore, the interviews were divided into the three aspects namely technical, economic, and social feasibility. Lastly, the interviews were analyzed in terms of technical, economic, and social feasibility using the literature review.

This study showed that energy density, and thus range, is one of the most important parameters for evaluating e-rickshaw batteries. Furthermore, the literature and case study demonstrated that the Indian battery market is highly price sensitive, which makes a low

energy cost per kWh of battery storage very important when aiming to be competitive. In contrast, the sea salt battery showed positive results in other aspects. The study showed that the sea salt battery outperformed commercial batteries, in terms of cycle life. More simulations and lab research need to be done on this, but this could potentially save drivers a lot of costs, if they have to buy a new battery much less frequently. In addition, it was found that the sea salt battery is suitable to be placed in an e-rickshaw. Furthermore, outcomes of the case study showed that it is desirable to integrate the sea salt battery with a BMS system, which facilitates and improves the operations of the e-rickshaw operators. Due to the very low toxicity of the sea salt battery, compared with its competitors, the sea salt battery performs very positively in terms of social acceptance. To conclude, sea salt batteries are feasible for use in e-rickshaws if the energy density and cost per kWh of battery storage are improved and come close to that of commercial batteries. The sea salt battery is an environmentally friendly battery source that, due to its long life and performance in hot climates, could potentially be promising for e-rickshaw drivers in India.

The data collection for the sea salt battery was largely based on the information provided by Dr. Ten. Therefore, a limitation of this study is that conclusions are drawn about technical, economic and social components of the sea salt battery, without the author's back testing of found parameters in literature and doing additional research. Moreover, it should be kept in mind that this study was conducted during the COVID-19 epidemic. Due to the pandemic, it was not possible to conduct the interviews in India in person and therefore an intermediary was used to conduct the interviews. A limitation of this study is that the author was not physically present in India and did not have close contact with the intermediary when the interviews were conducted. Had the author been more involved in the interviews conducted by an intermediary, he could have asked more pointed follow-up questions in order to get clearer answers

By examining the current state of the e-rickshaw market in India, the limitations of commercial batteries that are currently available, and the potential of the sea salt battery, this study showed the importance of the adoption of sustainable alternatives in the Indian battery market. Therefore, it would be of interest the Indian government to stimulate use of the sea salt battery for environmental reasons. This also aligns well with the Indian government’s plan to encourage the adoption and manufacture of electric vehicles. The research has shown that it would be interesting for Dr. Ten to investigate how they could design the sea salt battery so that it could be used at swapping stations.

Considering the great importance of range and charging time of the sea salt battery, it is recommended to further research the chemical properties and the charging and discharging behavior of the battery. Next, it would be worthwhile for future research to analyze the economic feasibility and payback period of a swapping station model to be used for the sea salt battery. Lastly, it is recommended to conduct a life cycle assessment of the sea salt battery. This may also validate the conclusion that the sustainable materials used in the sea salt battery could actually provide a competitive advantage in the Indian battery market.

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This thesis is the culmination of my master's degree in Sustainable Energy Technology at TU Delft. During the period when I started working on my thesis, I was also very concerned with cryptocurrencies. This fascinated me so much that much of my free time and also of my thesis time went into researching them. Combining work with a thesis has not been easy and without the help of my supervisors I would certainly not have succeeded.

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1. INTRODUCTION

1.1 CASE STUDY DESCRIPTION

In India, e-rickshaws or tuk-tuks are a common means of transportation. Nowadays, the country caters to over 60 million users every day (Express Drives Desk, 2020). The e-rickshaws are driven by electric motors energized by lead-acid batteries or lithium-ion batteries. In the study of Tirpude et al. (2020) it was found that 90% of the e-rickshaws in operation in New Delhi were based on lead-acid batteries, while lithium-ion batteries only made up for a 10% share. The popularity of both batteries stems from the fact that they are reliable and inexpensive compared to other battery technologies. However, the main concern regarding both e-rickshaw technologies is that the batteries fail far short of their expected battery lifespan. Also, the materials being used and the improper and careless handling of lead-acid and lithium-ion batteries after reaching their end-of-life, has unfavorable consequences for the environment (Zhang, Chen, Zhang, & Liu, 2016). Nevertheless, a new type of battery made from sea salt has recently been invented. This so-called sea salt battery was engineered to create a new sustainable battery technology. The sea salt battery could potentially be a better, cheaper, and greener battery for storing energy than lead-acid or lithium-ion batteries (Dr. Ten, 2019). Hence, it is interesting to perform a feasibility study to explore how the sea salt battery could become a feasible technology for electric rickshaws.

1.1.1 E-rickshaws as Last-Mile Connectivity in New Delhi

Nowadays, the country caters to over 60 million e-rickshaw users every day (Express Drives Desk, 2020). In the initial phase of the introduction of the e-rickshaw in Delhi, in 2010, auto-rickshaws, cycle-rickshaws and hand-pulled rickshaws were used as last-mile transportation (Harding & Kandlikar, 2017) (Shandilya et al., 2019). The e-rickshaw stemmed from the goal of offering an environmentally friendly version than the auto-rickshaw, while in terms of human effort it had to be less than in hand-pulled and cycle-rickshaws. (Ghosh et al., 2021). After their introduction, e-rickshaws became the most widely seen and used public vehicles in Delhi (Malik et al., 2018). Daily commuters prefer e-rickshaws over cycle-rickshaws, because they cost less, drive faster and are more comfortable (Ghosh et al., 2021) (Kumar et al., 2022). However, given their limited range and speed, they cannot compete with auto-rickshaws on trips which are longer than 5 kilometers, trips that often take freeways connecting different parts of the city. In contrast, e-rickshaws are widely accepted by commuters as a better alternative to gasoline or diesel cars for shorter distances because they are safer, cheaper and leave a smaller carbon footprint (Ghosh et al., 2021) (Kumar et al., 2022). Moreover, e-rickshaws are quickly and widely available in New Delhi and the-rickshaw design offers a larger passenger capacity (5–7 people) than auto-rickshaws (3 people) and cycle-rickshaws (2–3 people) (Kumar et al., 2022) (Harding & Kandlikar, 2017) (Ghosh et al., 2021).

1.1.2 Background of E-Rickshaw Operators in New Delhi

In this section, the background and status of the e-rickshaw in New Delhi on the social ladder will be discussed. Lahiri & Nath (2021) assessed in their study the socio-economic conditions and factors influencing the choice to become an e-rickshaw driver. They approached eighty-eight respondents, finding that 67% of e-rickshaw drivers were lower educated. Research found that rickshaw pullers are mostly migrant workers from rural areas who move to the city in search of work and better living conditions (Ghosh et al., 2021) (Kumar et al.,2022). Most rickshaw pullers are seasonal migrants, who divide their time between renting cycle-rickshaws in New Delhi and agricultural work (Harding & Kandlikar, 2017) (Kumar et al., 2022). Research by Malik et al. (2018) found that of the hundred e-rickshaw riders interviewed in New Delhi, half of this were unemployed or were cycle-rickshaw operators before owning becoming e-rickshaw driver. The other half consisted of daily factory or wage workers that were involved in higher physical work. Kokate et al. (2018) had similar findings, that unemployed, bicycle-rickshaw pullers, factory workers or day laborers involved in occupations such as painting or woodworking became e-rickshaw drivers to escape the low job security and the physical and hard work. It can thus be argued that e-rickshaw drivers are among the lowest class in India, which consists of low socio-economic groups and poor people, given the occupations that e-rickshaw drivers first held before becoming e-rickshaw drivers (Kumar et al., 2022).

However, Lahiri & Nath (2021) showed that 64% of e-rickshaw drivers surveyed indicated that they can support their families well with the income from their profession, indicating that the profession provides people with a secure and stable income. Other important factors for most drivers to enter the profession of e-rickshaw driver are that driving e-rickshaws required only minimal training, it has flexible working hours, and the profession is not age-related compared to other professions in the same social class (Lahiri & Nath, 2021) (Malik et al., 2018). Still, it should not be underestimated that an e-rickshaw driver's work is bad for his health, with chronic diseases such as tuberculosis common due to the continuous exposure to air pollution on the streets of New Delhi (Ghosh et al., 2021). Nonetheless, the main reasons for switching to driving e-rickshaws is that it gives people in India better social status, more income and less strenuous work (Kokate et al., 2018) (Kumar et al., 2022) (Pramanik & Rahman, 2019). Malik et al. (2018) and Lahiri & Nath (2021) showed that around 70% of e-rickshaw drivers became entrepreneurs to improve their social status. A sample survey (two hundred interviewees) conducted by Shandilya et al. (2019) in Delhi, found that 71% of e-rickshaw drivers owned the e-rickshaws while the remaining 29% drivers rented e-rickshaws.

The salary of an e-rickshaw driver in New Delhi is around the minimum wage, equivalent to about Rs. 559 per day (Business Today, 2022). On average, e-rickshaw drivers earn more than a cycle-rickshaw drivers and less than auto-rickshaw drivers. The studies Malik et al. (2018) and Kumar et al. (2022) found that the daily wage of e-rickshaw operators is between Rs. 550-800, which is higher than the daily wage of cycle-rickshaw operators which is between Rs. 300-450. The same studies found that the daily wage of auto-rickshaw drivers is between Rs. 700-1000, which is higher than the daily wage of e-rickshaw operators (Malik et al., 2018).

1.1.3 Stakeholder Map of Various Actors Involved

As part of this thesis, interviews were conducted with several actors. These actors include charging service providers, battery and e-rickshaw manufacturers, battery and e-rickshaw stores, and e-rickshaw drivers. For this reason, these actors are indicated in red in the stakeholder map. The remaining actors are indicated in blue and are beyond the scope of this study, which otherwise would have become too extensive. Figure 1 gives an overview of the stakeholder map with the various actors involved in the e-rickshaw industry in New Delhi (Singh et al., 2021).

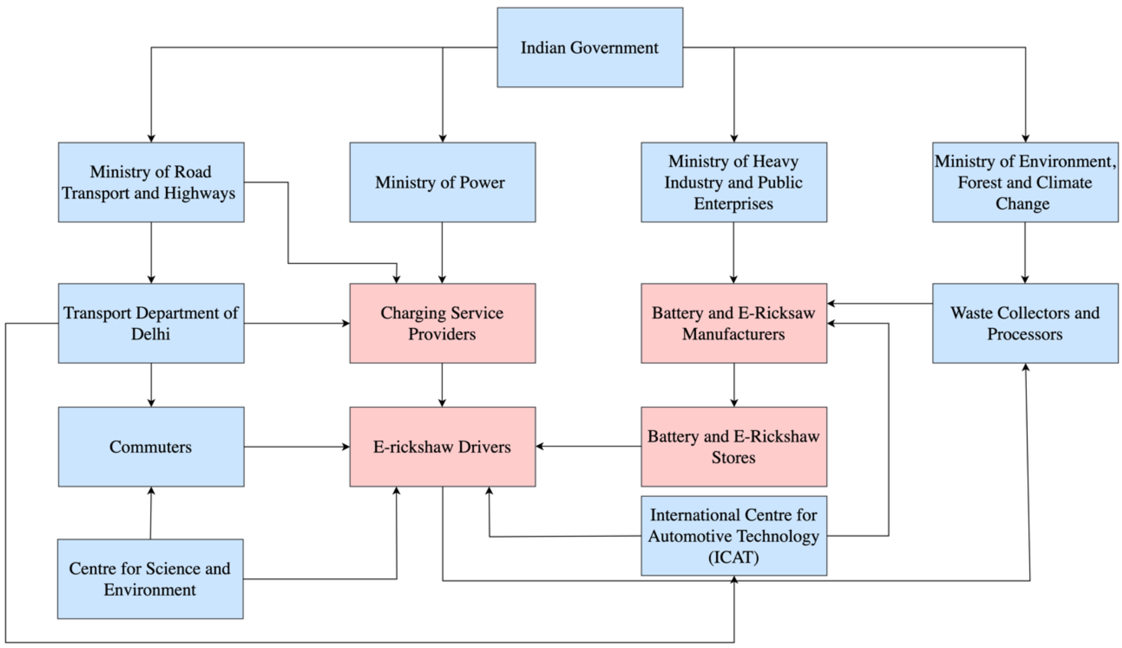

Figure 1. Stakeholder map of the various actors involved in the e-rickshaw industry in New Delhi

The Ministry of Road Transport and Highway formulates the standards and regulations for electric vehicles and is responsible to provide on charging infrastructure. The interest of the ministry is to combat air pollution and to boost e-rickshaws on roads to enhance last-mile connectivity. It is responsible for the Transport Department of Delhi and the charging services in Delhi.

The Ministry of Power is responsible for power supplies and grid management in India. Its role is to promote and encourage non-polluting vehicles by providing a robust power grid. It is responsible for supplying electricity to charging services in Delhi and implements the policy on it.

The Ministry of Heavy Industries and Public Enterprises is implementing policies for the production and operation of electric vehicles. The goal of this ministry is to make India a manufacturing hub for electric vehicles. It oversees and cooperates with battery and e-rickshaw manufacturers.

The Ministry of Environment, Forestry and Climate Change's function is to establish guidelines for the safe disposal and recycling of batteries. The goal of this ministry is to prevent air pollution by promoting electric vehicles such as e-rickshaws. It also aims to prevent soil and water pollution through the recycling of batteries. It oversees and interacts with waste collectors and processors.

Transport Department of Delhi implements policy by issuing mandates and investments for charging infrastructure and is also responsible for vehicle registration and licensing. It aims to combat air pollution by promoting safe, reliable and accessible means of transportation. It oversees the ICAT institution and enables commuters to travel safely in e-rickshaws.

The Center for Science and Environment conducts research and continues advocacy, lobbying and knowledge dissemination. The goal of this center is to combat pollution, guard the interests of commuters and e-rickshaw drivers, and promote social equality. As a result, it is in contact with both commuters and e-rickshaw drivers.

The International Centre for Automotive Technology (ICAT) is responsible for the assessment and development of e-rickshaw technology. Their goal is to promote the development of green technology and ensure safety. They therefore monitor battery and e-rickshaw manufacturers and e-rickshaw drivers for compliance with regulations and safety requirements

Waste Collectors and Processors are responsible for recycling old batteries. Their goal is to create a circular economy and prevent environmental damage by keeping old batteries from entering the environment. They collect old batteries from e-rickshaw drivers that are no longer being used. When processed, they provide battery manufacturers recycled batteries.

Charging Service Providers offer charging services. Their goal is to make a profit by selling electricity to non-polluting vehicles. This can be done by providing power but also by swapping batteries for e-rickshaw drivers.

Battery and E-Rickshaw Manufacturers are responsible for the assembly and production of batteries and e-rickshaws. They supply their goods to battery and e-rickshaw stores. Their goal is to sell batteries and vehicles and make a profit.

Battery and E-Rickshaw Stores provide batteries and e-rickshaws to e-rickshaw drivers. This can be done by selling them or by renting them by the day.

Commuters use e-rickshaw services, which provide a comfortable ride in a non-polluting vehicle. The reason commuters use the e-rickshaw is because of its cheap fare, easy accessibility and last-mile connectivity

E-Rickshaws Drivers operate the e-rickshaws. They earn money by driving commuters in an electric vehicle. They offer a solution to the last-mile connectivity problem and are an important mode of transportation in the energy transition to a more sustainable India with less greenhouse gas emissions.

1.2 RESEARCH PROBLEM

The e-rickshaws are driven by electric motors energized by lead-acid batteries or lithium-ion batteries. In the study of Tirpude et al. (2020) it was found that 90% of the e-rickshaws in operation in New Delhi were based on lead-acid batteries, while lithium-ion batteries only made up for a 10% share. The popularity of both batteries stems from the fact that they are reliable and inexpensive compared to other battery technologies. However, the main concern regarding both e-rickshaw technologies is that the batteries fail far short of their expected battery lifespan. Also, the materials being used and the improper and careless handling of lead-acid and lithium-ion batteries after reaching their end-of-life, has unfavorable consequences for the environment (Zhang, Chen, Zhang, & Liu, 2016). Nevertheless, a new type of battery made from sea salt has recently been invented. This so-called sea salt battery was engineered to create a new sustainable battery technology. The sea salt battery could potentially be a better, cheaper, and greener battery for storing energy than lead-acid or lithium-ion batteries (Dr. Ten, 2019). Hence, it is interesting to perform a feasibility study to explore how the sea salt battery could become a feasible technology for electric rickshaws.

1.3 PRACTICAL SIGNIFICANCE

In April 2015 and April 2019, the Indian government launched phases I and II of the FAME India Scheme, designed for the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles. Besides the stimulation for electric vehicles (EVs) for the adoption and manufacturing of them, setting up a charging infrastructure is one of the aims to support electric vehicles from all categories. Also, improving the electric public transport and reducing the levels of CO2 output are the other focus areas of these programs (Government of India, 2019). The National Mission for Transformative Mobility and Battery Storage announced in 2019 that after March 31, 2023, only electric tricycles and two-wheelers could be sold. Two years later, on March 31, 2025, all new sales should fall into the electric two-wheeler category (The Economic Times, 2019). The Indian government intended these plans to help achieve its goals for cleaner Indian cities, accelerate the insurmountable transition to electric vehicles and place India in a position to produce bases for electric two-wheelers and three-wheelers.

The practical relevance of this research lies in the exploration of how the sea salt battery can become a feasible battery technology for electric rickshaws. The feasibility of this battery has been tested from a technical, economic and social perspective. The goal is to contribute to the understanding of the sea salt battery system that could potentially serve as battery technology for electric rickshaws, the mode of transportation that will help accelerate and achieve India's climate goals.

1.4 THEORETICAL SIGNIFICANCE

The research areas of this study are the sea salt battery and battery electric rickshaws, using the methodology of a feasibility study to explore the technical, economic and social aspects. Regarding the scientific research papers, which can be found on Elsevier's Scopus, which is the largest database of peer-reviewed literature, different studies can be found about battery-driven electric rickshaws in India. Searching independently on the words "battery", "electric rickshaw", "feasibility study" and "India" yielded general information. However, when terms such as "sea salt battery," "rickshaw," "feasibility study," and "India" were (partially) combined, no results were produced. These terms are essential definitions in this research approach.

As for the literature on sea salt batteries, there is currently little to nothing on Elsevier's Scopus about feasibility studies for this type of battery. There is a significant knowledge gap regarding the study of feasibility of sea salt batteries integrated into e-rickshaws.

1.5 RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

This thesis aims to explore the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India. This thesis aims to approach this technology from a technical, economical and societal viewpoint. This way, a broad understanding can be formed regarding the technology's feasibility within the specific context of New Delhi. Therefore, this paper aims to answer the following research question:

How can the sea salt battery become a feasible technology for electric rickshaws in New Delhi, India?

In order to answer the main research question, the following sub-questions have been answered:

SQ1: *How can the sea salt battery become technically feasible for electric rickshaws?*
SQ2: *How can the sea salt battery become economically feasible for electric rickshaws?*
SQ3: *How can the sea salt battery become socially feasible for electric rickshaws?*

The main research question aims to explore the feasibility of the sea salt battery for electric rickshaws in New Delhi, India. In the first sub-question, relationships between commonly used battery energy sources in e-rickshaws in India and the sea salt battery, are approached from a technical viewpoint. This provides a clear overview of how the various technical components are related and how to determine if a new battery technology is technically feasible. The second sub-question explores the economic feasibility of the sea salt battery. The focus is on comparing the cost per kWh battery storage of lead-acid and lithium-ion batteries and exploring the cost per kWh battery storage of the sea salt battery. By comparing these battery technologies an estimate about the economic competitiveness of the sea salt battery can be made. The third sub-question explores the social feasibility of the sea salt battery. It then identifies the battery safety and the impact of lead-acid and lithium-ion batteries on the environment, while exploring the environmental impact of the sea salt battery.

1.6 ROLE OF RADS GLOBAL AND DR TEN

Independence from third party interests is critical for conducting objective research that complies with academic standards. However, this thesis was carried out under the guidance of Rads Global and Dr Ten. Although resources and expertise from both companies were used for this thesis, the research is independent from the individual interests of Rads Global and Dr Ten. The research design and outcomes were not influenced in favor of either company. Rads Global company focusses on coatings for glass surfaces of photovoltaic modules, causing the modules to increase performance while needing less water to clean these modules (Rads Global, 2022). Dr Ten focusses on product and process innovation within the sport, food, energy and chemical sectors. Example of products Dr Ten is currently working on are solar panels, batteries, ice skates, plastics, coatings, lubricants and sport nutrition (Dr Ten, 2015). The contacts and experience of Rads Global and the knowledge and guidance of Dr Ten were used to explore the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India.

1.7 REPORT OUTLINE

The remainder of this report will have the following outline: In Chapter 2 the theoretical basis of this thesis will be provided. In Chapter 3 the research approach and methodology will be discussed. Subsequently, Chapter 4 will present the findings from applying the research methodology. Lastly, Chapter 5 will discuss the main findings, the implications of the findings and the limitations of this thesis.

2. LITERATURE REVIEW

In this chapter, a literature review is displayed that enables the exploration of the feasibility of sea salt battery technology for electric rickshaws in New Delhi, India. This literature review determines how this thesis is embedded within existing literature and defines key concepts and theories, providing the scientific basis of this thesis.

2.1 REVIEW ON FEASIBILITY STUDY

Feasibility studies are used to provide a set of findings that help determine whether ideas should be recommended for further research and implementation. (Bowen et al., 2009). A feasibility study is an analysis of the viability of a project based on technical, economic and social factors relevant to the project, partly based on the three sustainable development pillars, economic, social and environmental (Bobba et al., 2018) (Bause et al., 2014) (Urkiaga et al., 2006). Shen et al. (2010) introduced an approach to conduct a feasibility study by taking into account the ecological, social and economic aspects. In this thesis, the economic and social aspects are examined as they overlap with the approach of Shen et al. (2010) and Urkiaga et al. (2006). In addition, the technical aspect is examined, which is relevant to exploring the feasibility of sea salt battery technology for electric rickshaws in New Delhi, India (Bause et al., 2014). The book on feasibility study of sustainable systems by Herriott (2014) is mainly used to determine how to perform each of the feasibility studies.

2.1.1 Technical Feasibility

In this section the technical feasibility of the sea salt battery will be explored. A comparison of the technical parameters of lead-acid, lithium-ion and the sea salt battery are made based on technical assessments found in literature (Peters et al., 2017) (Van den Bossche et al., 2006). In contrast, some papers show the use of HOMER software, a software application which can be used to design and evaluate technically and financially the options of battery technologies (Nair et al., 2010) (Amutha & Rajini, 2016) (Halabi et al., 2017). The use of this software is beyond the scope of this thesis, because more specific data is needed while this thesis focused on exploratory research. Ultimately, the battery type that will succeed in the market will depend on its performance relative to the alternative based on several key criteria, which are used to characterize a specific storage technology or system (Weinert, Burke & Wei, 2007). These characteristics could determine the compatibility of the storage with a proposed application. Technical parameters such as energy density, specific energy, the number of cycles a battery can withstand at a given discharge rate and maintenance requirements are widely used to compare the specifications of lead-acid and lithium-ion batteries (Benveniste et al., 2018) (Morris & Tosunoglu, 2012). The same metrics are used in feasibility studies by Lee et al. (2021), which assessed the technical feasibility and economics of reused batteries for electric vehicles for the purpose of capturing power surge. Khofiyah, Sutopo and Nugroho (2019) assessed the technical feasibility of a lithium-ion battery on these metrics, to support an unmanned aerial vehicle. The same technical assessment was also used in the paper of Ray et al. (2020), where they investigated the potential of battery-changing technology for e-rickshaws. Hereby, they first provided an overview of the different charging systems that were discussed and selected. For this reason, it was decided to use the same metrics to determine technical feasibility in this thesis. In determining the technical feasibility of a system, questions such as "how does the technology compare to other commercial technologies in terms of energy density and lifetime?" and "are there any limitations in placing the sea salt battery in an e-rickshaw?" will be addressed.

Based on these factors, it was explored how the sea salt battery could become technically feasible for e-rickshaws.

2.1.2 Economic Feasibility

For a sea salt battery to be economically viable as a battery technology for electric rickshaws, it must compete with commercial technologies in terms of price (Shen et al., 2020) (Vartiainen et al., 2020). Herriott (2014) mentioned in his book *Feasibility Analysis for Sustainable Technologies: An Engineering-Economic Perspective* that a path of calculating the total costs of production can be followed. Herriott stated that these methods are used to indicate the profitability of the technology, potential investments, or projects. The method used by Herriott (2014) calculates and compares several economic parameters such as the internal rate of return on investment (IRR), the net present value (NPV) and the net production costs (NPC) over the technology’s lifetime (Siddique et al., 2014) (Rotella et al., 2021). For instance, Jumare (2020) used these economic parameters, where the author conducted an economic evaluation of a saltwater battery energy storage system using a preliminary design. However, a disadvantage of this method might be that due to the lack of information on the cash flows, these measurement methods cannot always be used. In that case, assumptions are used that are sometimes inappropriate and make the outcome unreliable.

Another method that can be used to compare different battery technologies on economics is by studying the cost per kWh of battery storage (Dhundhara et al., 2018) (Kebede et al., 2021) (Madlener & Kirmas, 2017). During the economic feasibility study, the energy cost per kWh of battery storage (€/kWh) was used (Fan et al., 2020). The metric was used because it allowed a direct comparison of the different battery technologies. Furthermore, the battery prices of competitors on the Indian battery market were reviewed. Lastly, the analysis reviews the relative ratio of battery costs to the other costs borne by rickshaw drivers.

Finally, based on the comparison of the cost per kWh of battery storage, conclusions will be drawn how the sea salt battery could become economically feasible for e-rickshaws in New Delhi, India.

2.1.3 Social Feasibility

In general, social feasibility is a commonly used metric to determine the feasibility of a technology or product (Tang et al., 2019) (Bastholm, 2019). This study considered battery safety and the impact of environmental parameters on the environment to explore the social feasibility of the sea salt battery (Fan et al., 2020) (Bobba et al., 2018). Social acceptance is a perspective that plays a role in the acceptance of new technologies, involving the safety of these technologies. In contrast, potential risks are currently present in lead-acid and lithium-ion batteries, which contain toxic, hazardous, flammable and explosive materials. These materials can lead to numerous pollution accidents such as fires, explosions, poisoning and leaks. (Zhang et al., 2016) (Lisbona & Snee, 2011). Social feasibility also considered the environmental impact of commercial battery technologies, where the environmental impact of a technology is determined by using the global warming potential (GWP) and acidification potential (AP) to express social feasibility (Peters and Weil, 2018) (Yudhistira, Khatiwada, & Sanchez, 2022). These parameters are used to explore how the sea salt battery could become socially viable. Also, the battery safety will be compared between the different battery technologies.

Based on the analysis of battery safety and environmental impact, it is possible to explore whether the sea salt battery can become a socially feasible technology for e-rickshaws.

2.2 E-RICKSHAWS BATTERY LANDSCAPE

In 2016, the number of electric rickshaws plying on the roads in New Delhi was estimated to be over 100,000, where only 29% were registered from April 2013 to March 2017 (Ghate and Suneja, 2018) (Tirpude et al., 2020). Including other states, in 2014 it was reported that the e-rickshaw population in India was 1.5 million. Multiple bodies also reported that 15,000 e-rickshaws every month or under 200,000 e-rickshaws per annum could be added to this number (Businesswire 2019). It was calculated that the current fleet of e-rickshaws could be estimated at 2.9 million as of 2022. Prescient & Strategic (2020) reported that this fleet of e-rickshaws could increase by 15% per annum, amounting to an enlargement of 0.435 million per annum or 36,250 per month. These figures could be much higher, as a large percentage has not yet been registered.

These e-rickshaws in India are powered by batteries that serve as energy storage systems. There are two basic types of batteries: primary and secondary (Flowers et al., 2019). Primary batteries are single-use batteries because they cannot be recharged. The alkaline battery and the zinc-carbon battery are well known examples of this. Secondary batteries are rechargeable. These are the types of batteries found in devices such as smartphones, electronic tablets, and automobiles. Batteries can be used for stationary applications (energy storage, balancing networks) or for mobile applications (electronic devices, automobile industry). This thesis focused primarily on rechargeable batteries and did so in the electromobility field. Commercial rechargeable batteries include lead-acid (Pb-acid), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), lithium-ion (Li-ion) batteries (Liang et al., 2019). Presently, most used batteries in electric-rickshaws are Pb-acid and Li-ion batteries (Kumar & Bharj, 2020) (Tirpude et al., 2020). Lead-acid batteries have been used in e-rickshaws from the beginning. In the study of Tirpude et al. (2020) it was found that most of the e-rickshaws in operation, namely 90%, are based on lead-acid batteries, while lithium-ion batteries are made up for the other 10% share. Therefore, the lead-acid and lithium-ion battery will be in the scope of this thesis. Both battery technologies have advantages and disadvantages. These and the technology itself will be discussed. Finally, the sea salt battery will be thoroughly reviewed.

2.2.1 Lead-Acid Battery

The lead-acid battery was invented by French physicist Gaston Planté in 1859 and is known as the first commercially successful rechargeable battery. Even though it is a relatively old technology compared to others, the Pb-acid battery is still widely used these days, because of its low cost, low self-discharge rate, high discharge currents, and good low-temperature tolerance. Therefore, the Pb-acid battery is very suitable for applications like portable electronic devices and electric vehicles (Liang et al., 2019).

The lead-acid battery uses lead (Pb) as the anode, lead dioxide (PbO_2) as the cathode, with sulfuric acid (H_2SO_4) as an electrolyte. The following half-cell reactions take place inside the battery cell during discharge:

$$At\ the\ anode: \quad PbO_2 + 3H^+ + HSO_4^- + 2e^- \rightleftharpoons 2H_2O + PbSO_4 \quad (2.1)$$
$$At\ the\ cathode: \quad Pb + HSO_4^- \rightleftharpoons PbSO_4 + H^+ + 2e^- \quad (2.2)$$
$$Overall: \quad Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O \quad (2.3)$$

During the charging process, the reactions at each electrode are reversed; the anode becomes the cathode, and the cathode becomes the anode. It was found that in the fully discharged state, both the anode and cathode become $PbSO_4$. The electrolyte loses much of its dissolved H_2SO_4 and becomes water, primarily. While in the fully charged state, the cathode and anode consist of PbO_2 and Pb, respectively. The electrolyte turns back to concentrated H_2SO_4. When in the fully charged state, the battery stores most of the electrochemical energy. This can be seen in Figure 2.

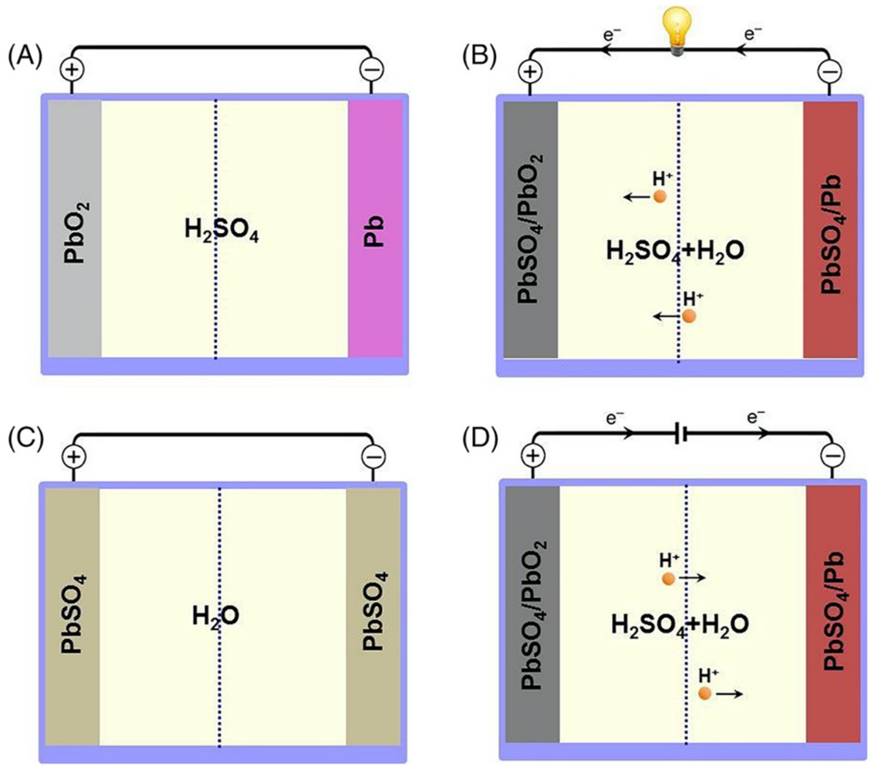

Figure 2. Schematic illustration of the lead-acid battery in different operational conditions: A, fully charged state, B, discharge process, C, fully discharged state, and D, charge process (Liang et al., 2019)

However, Pb-acid also has a number of drawbacks. The main deficiencies of Pb-acid batteries are their relatively short lifetime and their low energy density compared to other commercial batteries (Liang et al., 2019). They have the lowest specific energy storage capacity among Ni-Cd, Ni-MH, and Li-ion batteries, and usually have a larger specific weight. This indicates that Pb-acid batteries store the least amount of energy per unit weight. Another flaw is the limited discharge capacity these batteries have, where only 30% to 50% of the rated capacity of a typical Pb-acid battery can be used. For example, a battery with a capacity of 800 Ah can, at best, provide only 400 Ah of real capacity. When draining the batteries more than this, irreversible damage occurs and thus affects the battery life negatively and accelerates the battery breakdown (PowerTech, 2020). Furthermore, Pb-acid batteries suffer from slow and inefficient charging rates and have limited temperature stability. Lastly, both the lead and the acid used in the battery are very toxic for humans and the environment. Lead is persistent, meaning that it cannot be broken down by most plant and animal life, so once it is in the food-chain it remains there. Hence, if the right precautions are not taken during manufacturing and usage, or spent batteries are not properly disposed of, there could be considerable health risks (Gottesfeld et al., 2018) (Chen et al., 2012).

2.2.2 Lithium-Ion Battery

The lithium-ion (Li-ion) battery was invented in the 1970s and after Sony's commercialization of the lithium-ion battery in 1991, the adoption of this technology took off (Kandeeban et al., 2020) (Albright, Edie, & Al-Hallaj, 2012). Lithium-ion batteries are well-known for their high energy density, which is better than other commercial batteries technologies. This can be seen in Figure 3. Also, compared to lead-acid, this technology has a higher depth of discharge and the charge and discharge current density is better, making lithium-ion batteries charge faster.

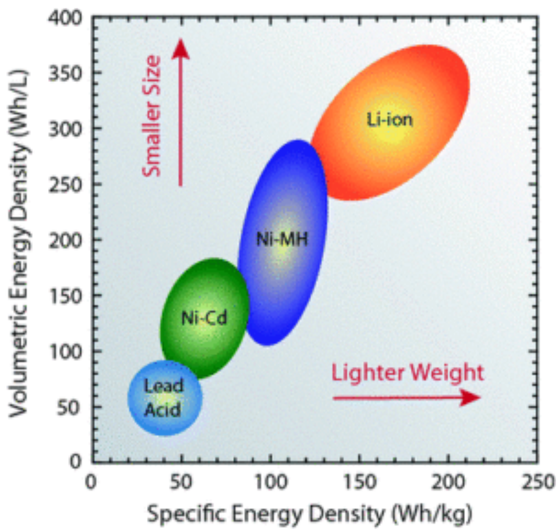

Figure 3. Diagram of the specific energy density and volumetric energy density of commercialized battery types (DiLeo, 2012)

In addition, lithium-ion batteries have a longer lifetime and higher efficiency than most other types of battery. (Qadrdan, Jenkins & Wu, 2018). These features make them the most widely used rechargeable batteries in portable electronic devices, and they are increasingly used in electric vehicles. (Ministerie van Infrastructuur en Waterstaat, 2020). Governments of many countries, including India, recently announced policies to boost sales of electric vehicles (EV), which will have a positive impact on the growing market share of lithium-ion in rechargeable batteries (Government of India, 2019). For instance, in 2019 the Indian government approved the National Mission on Transformative Mobility and Battery Storage, a roadmap for implementing battery manufacture in the country (Kenning, 2019). In May 2021, India approved a Production Linked Incentive (PLI) scheme to promote the manufacturing, export, and storage of lithium-ion cells, which is essential for the development of electric vehicles (Indian Ministry of Mines, 2021).

The lithium-ion battery uses graphite (C) as the anode. Metal oxides, such as lithium cobalt oxides ($LiCoO_2$), lithium nickel oxides ($LiNiO_2$), lithium iron phosphate ($LiFePO_4$) and lithium manganese oxides ($LiMn_2O_4$) are mostly used as the cathode. $LiCoO_2$achieves the best results and is the most common combination, but it is very expensive, toxic and has a small range where it can be stable. Lithium salts dissolve in organic solvents, being the liquid electrolytes for conventional lithium-ion batteries (Yang et al, 2021) (Liang et al., 2019). It is possible to replace the liquid electrolytes with polymer electrolytes. $LiCoO_2$ and C are used as the representative cathode and anode materials, respectively, to describe the basic chemistry of lithium-ion batteries. The reversible electrochemistry reactions are shown as follows:

$$At\ the\ anode: \quad C + xLi^+ + e^- \rightleftharpoons Li_xC \tag{2.4}$$
$$At\ the\ cathode: \quad LiCoO_2 \rightleftharpoons Li_{1-x}CoO_2 + xLi^+ + e^- \tag{2.5}$$
$$Overall: \quad LiCoO_2 + C \rightleftharpoons Li_{1-x}CoO_2 + Li_xC \tag{2.6}$$

During the charging process, the reactions at each electrode are reversed; the anode becomes the cathode, and the cathode becomes the anode. During a discharge cycle, lithium atoms in the anode are ionized and separated from their electrons. The Li^+ ions move from the anode and pass through the electrolyte until they reach the cathode, where they recombine with their electrons and electrically neutralize. This can be seen in Figure 4.

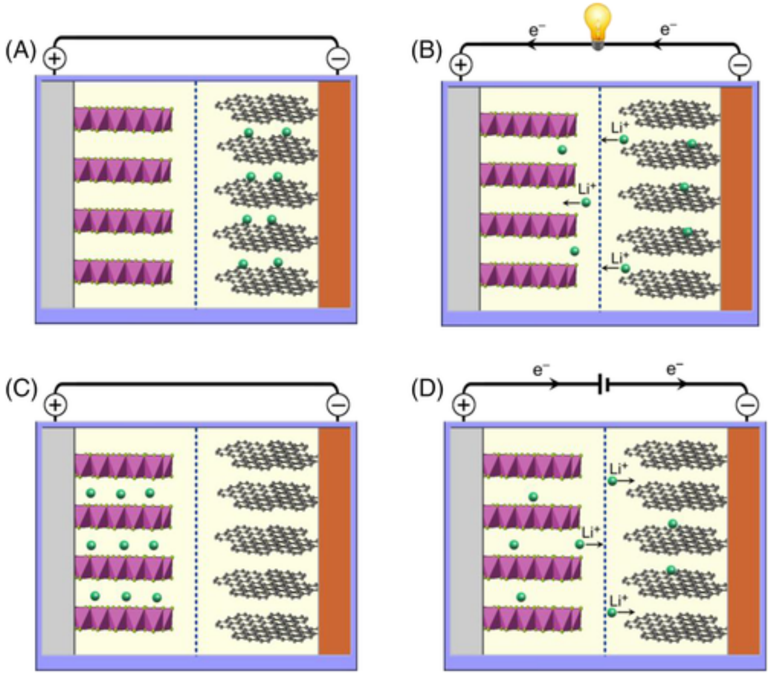

Figure 4. Schematic illustration of Li-ion battery in different operational conditions: A, fully charged state, B, discharge process, C, fully discharged state, and D, charge process

The lithium-ion battery has some imperfections as well. Like Pb-acid, Li-ion cells have a limited lifetime. Deep discharging or over-charging of Li-ion cells must be avoided to ensure sufficient lifetime and the operational safety of these batteries. The life of the battery will decrease if the depth of each discharge is more then 80% of the rated capacity. (Albright, Edie, & Al-Hallaj, 2012) (Prochazka et al., 2016).

As stated above, cobalt is used in Li-ion batteries but, compared with other transition metals, it is less abundant and widely spread across the world. Therefore, this metal becomes more expensive, while being present in politically unstable countries, with ethical issues concerning the way it is mined in Congo (Sovacool, 2019). It cannot be overlooked that more than 50% of cobalt is mined in Congo, which is a reason for concern. In addition, China currently controls the processing of nearly 60% of the world's lithium, 35% of nickel, 65% of cobalt and more than 85% of rare-earth elements, making the world increasingly dependent of China (Schreffler, 2021). Moreover, the energy transition means that the demand for lithium and cobalt will increase by a factor of 3 between 2017 and 2025 (Ministerie van Infrastructuur en Waterstaat, 2020). The rising prices and the scarcity of the raw materials for lithium-ion batteries are therefore a problem. The resulting higher manufacturing costs subsequently cause higher prices when comparing it with other secondary battery technologies (Liang et al., 2019)

Another disadvantage is that most types of Li-ion batteries contain a variety of combustible materials, which could suffer a thermal runaway. The Li-ion batteries tend to overheat and can be damaged at high voltages. The risk of thermal runaway and combustion, where the battery can burst into flames, must be avoided. This shows that these batteries are sensitive to high temperatures. (Golubkov et al., 2014). A Battery Management System (BMS) is therefore needed, which is a circuit co-operating with the charger, forbidding deep discharging of the cells present in battery packs (Prochazka et al., 2016). So, Li-ion batteries need additional protection circuits to limit voltages and currents to ensure safe operations (Liang et al., 2019). Another downside is that Li-ion batteries lose their capacity and cycle life when stored in temperatures over 30°C for an extended period (Liang et al., 2019).

It is inevitable that when Li-ion batteries reach the end of their battery life, spent batteries will remain. Due to numerous burnable organic and toxic substances from used batteries, simply landfilling spent batteries would harm the environment and human health. Therefore, proper handling and recycling, along with reusing the many valuable metals, such as cobalt, nickel and lithium is needed to reduce pollutants. Consequently, recycling is of major importance for the sustainable and commercial viability of Li-ion production, alongside its environmental impacts. However, making these processes feasible and commercially viable is difficult (Yang et al, 2021).

2.2.3 Sea Salt Battery

There are more sustainable and environmentally friendly alternatives than the battery technologies described above. The sea salt battery is an example of this, which is a sustainable and environmentally friendly battery that was developed at Dr. Ten in 2008 (Dr. Ten, 2019). The discovery of this battery is a result of academic research on secondary zinc-air batteries (Ten Kortenaar et al., 2021). Primary (i.e., not rechargeable) zinc-air batteries have been widely used as commercial batteries since their introduction in 1932. Research was done to develop a secondary (i.e., rechargeable) zinc-air battery, which has great potential because of its high energy density and potentially very low manufacturing cost, compared to lithium-ion batteries (Zhang et al., 2019). However, the difficulties associated with air cathodes and zinc anodes have kept their potential untapped so far. The research to overcome these challenges is still in progress (Li et al., 2019). Pelt's (1994) research on zinc-air batteries proved to be an important building block for the development of a possible variant of the zinc-based secondary battery, the sea salt battery (Ten Kortenaar et al., 2021).

The sea salt battery was so named because the main component of the electrolyte is sea salt (Dr Ten, 2019). The sea salt battery refers to a new, clean battery that is made from water, sea salt, graphite, and a range of additives and salts containing metal ions (Ten Kortenaar et al., 2021). The sea salt battery is green (safe, non-toxic and produced from recyclable materials) and has potential for different reasons. First, the background in sea salts as electrolytes make them green, low-cost and recyclable. Second, it uses relatively cheap, natural carbon electrode materials while leaving out the strong acids and lead toxins. Moreover, the battery can stand high temperatures, has a long lifetime, can be discharged 100% and can be made from local sea salts, minerals and graphites. The disadvantages of the sea salt battery have to do with its large size, low energy density and the fact that it is still in a development stage without being in mass production.

Materials are stored in sealed bags with two graphite contacts coming out of the cells. This can be seen in Figure 5. The electrochemistry does not require membranes, which are used in other battery technologies, only low-cost separator bags. The reactions inside the cells are highly reversible. Simple connectors and a plastic box or bag size of choice make customized batteries feasible.

Figure 5. Illustration of the sea salt battery enclosures

Also, the battery can be connected directly DC-DC to solar panels, making it easy to also directly integrate the battery in solar panels. For these reasons, the sea salt battery may be well suited for off-grid energy storage (Ten Kortenaar et al., 2021).

2.3 CONCLUSION

This thesis aims to fill an identified scientific knowledge gap by exploring the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India. Therefore, a feasibility study was performed whereby the technical, economic, and social aspects were discussed. To explore the feasibility of the sea salt battery, it will be compared with lead-acid and lithium-ion batteries whereby the chemistry and the pros and cons will be discussed.

3. RESEARCH METHODOLOGY

In this chapter, the research approach and its rationale are presented. Subsequently, the research strategy per sub-question is provided. Thereafter, the case study methodology, methods for data collection and methods for data analysis are discussed.

3.1 RESEARCH APPROACH

This thesis aims to explore the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India, in order to answer the following main research question:
How can the sea salt battery become a feasible technology for electric rickshaws in New Delhi, India? The research approach is exploratory and aims to describe and understand the feasibility of using a sea salt battery in electric rickshaws.

The research problem is approached in a mixed-method manner, which fits the objective of this thesis. Qualitative and quantitative methods are therefore involved. The mixed methods approach is useful because by combining qualitative and quantitative methods, a synergy can be created for better understanding of the research topic, yielding more knowledge than performing only one of these methods (Ivankova, Nataliya & Creswell, 2009) (Stange et al., 2006). The mixed methods approach is applicable for this thesis as it allows further examination of the problem at different levels. The quantitative methods focus on identifying the differences in parameters and costs of the batteries, so that they are easier to compare. The qualitative methods complement this because they have the advantage of taking into account the complexity of the transition to the sea salt battery. Combined, these methods provide the information needed to explore the feasibility of using the sea salt battery in electric rickshaws.

3.1.1 Research Scope

The research scope of the study refers to the boundaries within this research project that will be performed. To define the scope, aspects that will be covered in this thesis are defined. Within this study, the scope of the research is: technical, economic and social feasibility. Furthermore, aspects as e-rickshaws, batteries, sustainable energy transition and New Delhi are considered during this thesis.

3.1.2 Research Strategy per Sub-Question

This answering of the main question of this thesis can be divided into three sub-questions. A visualization of the research strategy is provided in Figure 6. Subsequently, the case study methodology (section 3.2) and the associated methodologies for data collection (section 3.3) and analysis (section 3.4) are discussed.

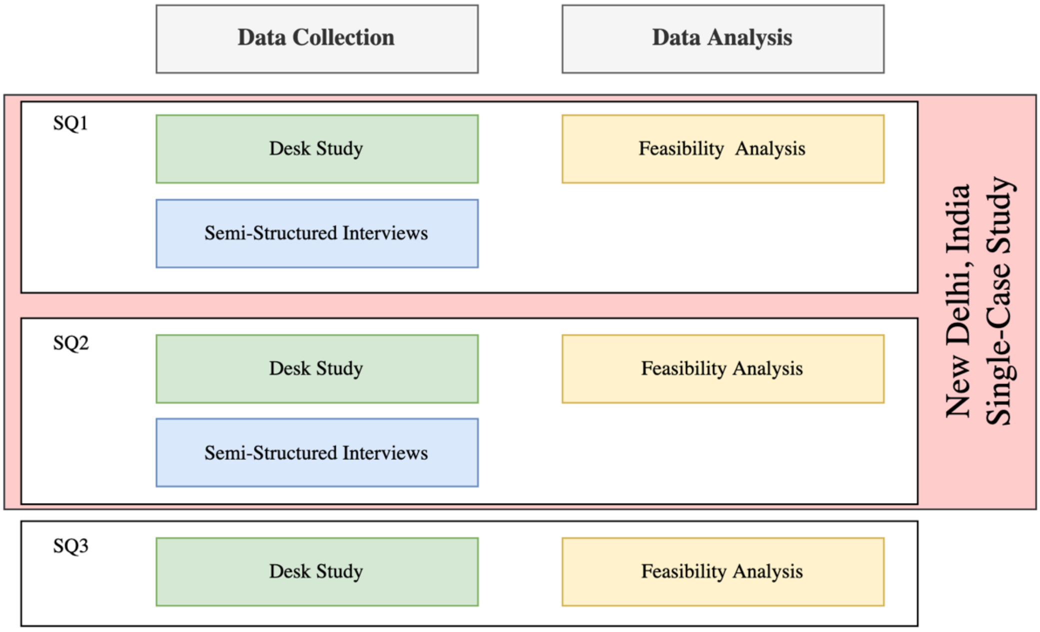

Figure 6. Visualization of the research strategy per sub-question and corresponding methods

SQ1: How can the sea salt battery become technically feasible for electric rickshaws?

In order to answer the first sub-question, a desk study was conducted for data collection regarding the characteristics of the most used battery technologies in e-rickshaws in New Delhi, India. Subsequently, semi-structured interviews were conducted to determine the important parameters of the different battery technologies. By identifying the different characteristics and parameters, it was possible to compare the battery technologies on a technical level. A feasibility analysis was then used to analyze and explore how the sea salt battery technologies could be technical feasible for e-rickshaws.

SQ2: How can the sea salt battery become economically feasible for electric rickshaws?

For the purpose of answering the second sub-question, a desk study was conducted for data collection. In addition, semi-structured interviews were conducted to determine the cost structure and revenue streams from e-rickshaw operators in New Delhi. Also, other stakeholders were interviewed. These interviews provided insight into the economic feasibility of the sea salt battery. A feasibility analysis was used to analyze the data.

SQ3: How can the sea salt battery become socially feasible for electric rickshaws?
To answer the third sub-question, a desk study was conducted to gain more knowledge about the social and environmental impacts of the batteries examined. Subsequently, by means of a feasibility study the social feasibility was analyzed.

3.2 CASE STUDY METHODOLOGY

Sub-question 1 and 2 are answered in chapter 4, using the single-case study methodology. Contrary to a single-case study, in a multiple-case study, researchers study multiple cases to understand the differences and the similarities between the cases (Baxter & Jack, 2008). In this thesis, the single-case study approach is used to gain more knowledge about one specific subject (Baxter & Jack, 2008). Case studies are intended to highlight the specifics from the viewpoint of the attendants, by using multiple sources of data. In contrast, when conducting a case study, the data collection and analysis methods are known to hide some details (Tellis, 1997).

There are different typologies regarding case studies. Lijphart (1971), Eckstein (1975) and Levy (2008) produce different classifications of case studies (Levy, 2008). However, this thesis will use the typology of Yin (2009). According to the typology of Yin [2009], there are three types of case studies:

- Exploratory: the case study is used to explore a particular phenomenon within its context.
- Descriptive: the case study is used to describe a particular phenomenon within its context.
- Explanatory: the case study is used to provide an explanation for a particular phenomenon within its context.

Next to a literature review, an exploratory case study was conducted to explore the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India.

3.2.1 Case Selection

Case selection is an essential component of the case study. This thesis conducted its case study in New Delhi, India, which created clear boundary conditions due to its specific geographical area (Yin, 2009). The capital of India was selected for this case study because India houses the biggest fleet of e-rickshaws worldwide (The Economic Times, 2018). The second reason for choosing this region was because Rads Global and Dr. Ten have a strong interest in this particular region, as many enterprise opportunities are occurring in the country, in its transition process to the use of more electric vehicles (Government of India, 2019) (The Economic Times, 2019).

3.3 DATA COLLECTION

In order to collect data for answering the sub-questions, data collection methods were applied. The methods involved desk research, including literature and desk studies, and semi-structured interviews.

3.3.1 Desk Study

A desk study was conducted in order to collect the data serving as input for data analysis, see section 3.4. First, a literature review was done to collect the technical parameters of the battery technologies for e-rickshaws and the sea salt battery to answer sub-question 1. Furthermore, papers were studied in order to collect data regarding the profitability of the battery technologies, and to calculate and compare several economic parameters. This data will serve as input in sub-question 2. Lastly, data regarding environmental impact and battery safety was gathered by studying various life cycle assessment papers. The data regarding these papers serve as input for sub-question 3.

3.3.2 Semi-Structured Interviews

Semi-structured interviews with several stakeholders were conducted in order to collect and verify data serving as input for data analysis, see section 3.4. Semi-structured interviews were conducted among the stakeholders involved in the e-rickshaw sector. According to Nelson (2009), there are three types of interviews used as tools for the collection of data: structured, semi-structured and unstructured. Structured interviews use closed-ended questions and the interviewee is therefore limited in their responses. Unstructured interviews have little structure with open-ended questions, which leaves more room for extended answers. Lastly, in semi-structured interviews, some of the questions asked are determined prior to the interview (Nelson, 2009). The order in which the questions are asked is flexible and respondents are completely free to answer. Also, the interviewer can continue to question answers. This can lead to more and new meaningful data (Kallio et al., 2016). For this reason, semi-structured interviews are the most appropriate approach for this thesis. The interviews were conducted in a semi-structured manner, to make the interview flow as smoothly as possible, just like an ordinary conversation. sing this approach it was also intended to gain trust between the interviewer and interviewee and to attempt to diminish the bias of the interview. However, there are also disadvantages to the semi-structured interview approach. The interviewee's willingness to cooperate greatly affects the course and outcome of data (Bolderston, 2012). The format of the pre-determined questions was the same for all interviewees, to validate the outcomes with each other (or not) and thus give a better picture. The interview guide is included in Appendix A.

Interviewees

Online interviews were conducted with several entrepreneurs who largely operate in New Delhi. Over a period of three months, a total of fifteen online interviews were conducted with stakeholders in the e-rickshaw domain in New Delhi. Table 1 shows the names of these companies, as well as their industry and their products and services. All interviewees gave their approval for displaying their interview outcomes.

Table 1. Characteristics of the interviewed companies or institutions.

Company or institutional name	Industry	Number of interviews
Individuals	E-rickshaw drivers	5
Goenka Electric Vehicles	E-rickshaw manufacturer	1
Indian Institute of Technology Delhi	University	1
Lithion Power	Battery swapping	1
Mobilytics	Battery swapping	1
Delhi Metro Rail Corporation Ltd.	Charging operator	1
ETO Motors	Charging operator	1
Dr. Ten	Battery manufacturer	2
Local shops	Battery shop	2

The structure of the interviews was set using a pre-formulated list of subjects and corresponding questions. Supplementary questions were formulated during the interview, whenever the interviewee brought up relevant new topics. Hence, the interviewee was allowed to direct the conversation, while the interviewer held a checklist of the topics. Some of the new topics were included in the list of interview questions, resulting in continuous updates and improvements in the interviews. The duration of the interviews lasted between one hour and three hours, which was also dependent on the available time of the interviewee. Directly after the interview, a summary was made. In addition to a summary, the main outcomes of the interview were written down in response to the questions asked.

3.4 DATA ANALYSIS

To analyze the data in order to answer the sub-questions, a data analysis method was used. The method includes a feasibility analysis.

3.4.1 Feasibility Analysis

A feasibility analysis was conducted throughout this thesis, in order to answer all the sub-questions and subsequently, the main question. The feasibility study conducted is an analysis of the feasibility of a project based on technical, economic, and social factors relevant to the project. To explore how the sea salt battery could become feasible for e-rickshaws, these factors are examined.

The feasibility analysis started with reviewing the summarized interviews. Furthermore, the interviews were divided into the three aspects namely technical, economic, and social feasibility. Subsequently, the analysis was conducted in several steps. The analysis began by summarizing the interviews conducted. Fifteen interviews were summarized in the order of the questions and answers asked during the interview, which can be found in Appendix A. Lastly, the interviews were analyzed in terms of technical, economic, and social feasibility using the literature review presented in section 2.1.

3.5 CONCLUSION

This thesis is divided into three sub-questions in order to answer the main research question: *How can the sea salt battery become a feasible technology for electric rickshaws in New Delhi, India*? An exploratory case study approach was used during this thesis, to explore the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India. This approach aimed to define and find out which factors are important to make the sea salt battery feasible for e-rickshaws. To answer the sub-questions about the technical and economic feasibility, data was collected via a desk study and via semi-structured interviews. In addition, data collection for the social feasibility sub-question was done through a desk study. The semi-structured interviews were conducted in a single-case study, in the region New Delhi, India. The analysis of the collected data was done through a feasibility analysis.

4. FEASIBILITY ANALYSIS

With the research methodology and case study design explained in the previous chapter, the conducted case study can be used to explore how the sea salt battery for e-rickshaws in New Delhi could become technically, economically and socially feasible. This chapter describes and analyzes the findings collected with the desk study and semi-structured interviews. Subsequently, it will answer the three sub-questions, as articulated in chapter 3.

4.1 TECHNICAL FEASIBILITY

This section addresses the technical parameters of commercial batteries. In accordance with these characteristics, the comparison was made between the highlighted battery technologies and the sea salt battery to determine its technical feasibility. The first sub-question *How can the sea salt battery become technically feasible for electric rickshaws?* is answered within this section by applying the methods discussed in chapter 3.

4.1.1 Competitiveness with Commercial Batteries

According to Peters et al. (2017) and Van den Bossche et al. (2006), technical parameters are used to assess different battery chemistries, which differ on fundamental assumptions and the use of different electricity mixes or system boundaries. Hence, to determine how the sea salt battery for e-rickshaws can become technical feasible, it is compared to the technical parameters of the most used battery technologies in e-rickshaws in India. Weinert, Burke & Wei (2007) found that the battery type that succeeds in the market will depend on its performance, relative to the alternative based on the several key criteria. Table 2 provides an overview of the technical parameters used to compare the different battery technologies on technical aspects. Moreover, the technical parameters shown in Table 2 were used as comparators because they are relevant for e-rickshaw operators when they have to decide which battery technology to use in their vehicle (Benveniste et al., 2018) (Morris & Tosunoglu, 2012). Interviews revealed that the most important issues for the battery of an e-rickshaw were the range and the charging time (Interview ETO Motors & Lithium Power). On this basis, the range of batteries was analyzed by comparing the energy density of battery technologies. Due to the short time available for all interviews, it was decided to do not research the charging. Therefore, the analysis of charging time is beyond the scope of this thesis.

Table 2. Comparison of batteries based on different literature and interviews (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021) (Interview Dr. Ten)

	Lead-acid	Lithium-ion	Sea salt
Energy Density (Wh/L)	100-150	200-250	8-20
Specific Energy (Wh/kg)	30-50	100-190	20-50
Cycle life (80% discharge)	200-300	500-2,000*	64,000**
Discharge capacity	50%***	80%***	100%
Temperature window	-20 to 50°C	0 to 45°C	-30 to 80°C
Complex BMS needed	Yes	Yes	No****
Invented in	Late 1800s	1991-1999*	2008

Note:

* Wide range because it depends on the metal oxide being used (cobalt, manganese or phosphate for instance).

** Cycle life at 100% discharge rate, at 80% discharge rate the cycle life would be much higher.

*** Discharging to a lower percentage is possible, however, irreversible damage to the battery occurs.

**** No complex BMS is needed considering direct charging from a solar panel. When using in an e-rickshaw, BMS might be needed.

To give a clear overview between the batteries being compared, the parameters energy density, specific energy, the cycle life, the discharge capacity and the temperature window in which the battery can operate without damaging the battery, were used (Peters et al., 2017) (Van den Bossche et al., 2006)

Comparison of the energy densities

The energy density (Wh/L) and specific energy (Wh/kg) of batteries are often used to compare different energy storage technologies (Peters et al., 2017) (Van den Bossche et al., 2006). These parameters relate storage capacity to the size or mass of the system, and essentially indicate how much energy (Wh) can be stored per unit cell, unit mass (kg), or unit volume (liter) of the material or device. Table 2 shows that lithium-ion batteries perform best in this regard, when comparing their energy density of 200-250 Wh/L with the 100-150 Wh/L of lead-acid batteries and the 8-20 Wh/L energy density of the sea salt battery (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021). The same is true for specific energy, with the lithium-ion battery performing best at 100-190 Wh/kg, followed by the lead-acid battery at 30-50 Wh/kg and finally the sea salt battery with specific energy between 20-50 Wh/kg (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021).

Based on this information, it was shown that the sea salt battery was outperformed by commercial batteries in terms of the energy density. Surprisingly, however, the sea salt battery performed almost as well as lead-acid batteries in terms of specific energy. Compared to lithium-ion, where the lowest specific energy is 100 Wh/kg, the sea salt battery, where the highest specific energy is 50 Wh/kg, is only one factor of two away, in terms of specific energy (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021). In addition, it should be taken into account that the discharge capacity of both lead-acid and lithium-ion is not equal to 100% (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021). Considering the previous and the comparison on specific energy, the sea salt battery actually performs better than lead-acid. This is due to the fact that, with a discharge capacity of 50%, the specific energy of lead-acid batteries achieves 15-25 Wh/kg. Moreover, the same calculation can be applied to the lithium-ion battery, which has a discharge capacity of 80%, bringing the specific energy to a range of 80-152 Wh/kg (Interview Dr. Ten). Hence, this shows that the specific energy density of the sea salt battery is closer to that of commercial batteries.

Comparison of the cycle life

When comparing the cycle times of the batteries, Table 2 shows that the sea salt battery performs better. During a laboratory test, the sea salt battery managed to perform 64,000 cycles while being 100% discharged (Ten Kortenaar et al., 2021) (Interview Dr. Ten). Whereas 2,000 cycles represent about 5 years of life for lithium-ion batteries, 64,000 cycles represent about 20 years of life for the sea salt battery (Ten Kortenaar et al., 2021) (Fluxpower, 2022). The manufacturer of the sea salt battery, Dr. Ten, even decided to stop the experiment, despite the end of the battery not being yet in sight (Interview Dr Ten). Hence, the end-life of the sea salt battery has not yet been found. This could potentially keep e-rickshaw operators from often having to buy a new battery for the e-rickshaw, which would save a considerable amount in costs over the years. Overall, the comparison showed that the battery life of the sea salt battery is very promising. Nevertheless, it should be noted that there is a difference between the lab test performance and the actual performance of batteries in the field when placed in the e-rickshaw.

When comparing the 64,000 cycles with the range of 200-300 cycles of lead-acid batteries, and the range of 500-2,000 cycles of lithium-ion batteries, it is noticeable that there is a big difference in lifespan (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021). Additionally, Table 2 shows that, for the cycle life, a discharge capacity of 50% is used for lead-acid and 80% for lithium-ion batteries (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021). In contrast, during the sea salt battery life tests, a discharge capacity of 100% is used (Ten Kortenaar et al., 2021) (Interview Dr. Ten). In other words, the difference in lifetime with the commercial batteries would be much higher if the same discharge capacity was used, which speaks in favor of the sea salt battery. Thus, from the comparison with other commercially available batteries, it can be concluded that the life of sea salt batteries is much better than lead-acid and lithium-ion batteries.

Comparison of the necessary Battery Management System

Considering the parameters displayed in Table 2, it shows that the sea salt battery can fully discharge and does not need a BMS system to protect the battery (Ten Kortenaar et al., 2021). The reactions in the sea salt battery are highly reversible and stable. This is one of the reasons it is possible to completely discharge this battery (Ten Kortenaar et al., 2021). This differs greatly from lead-acid and lithium-ion batteries, which need a BMS to prevent them from deep discharging and helps keeping the battery safe and work properly (Lee et al., 2021) (Kebede et al., 2021). For instance, depending on the application and the place of use, some lithium-ion batteries may be equipped with heating or cooling systems. The BMS system inside the battery activates or deactivates them as required by the battery and vehicle status (Flash Battery, 2022).

Compared to the other battery technologies, Table 2 shows that the sea salt battery has a much wider operable temperature range, ranging from -30 to 80°C (Ten Kortenaar et al., 2021) (Interview Dr. Ten). Lead-acid batteries have a temperature window from -20 to 50°C, while lead-acid batteries are operable in temperatures between 0 to 45°C (Lee et al., 2021) (Ten Kortenaar et al., 2021). The wide temperature window of the sea salt battery is beneficial in hot climates like India, because hot temperatures shorten the lifespan of batteries. As the temperature increases in the battery, so does the speed of the chemical reactions within the battery. The increase in chemical reaction speed can increase the output of the battery, but also increases the speed of battery degradation (Midtronics, 2022). Therefore, it can be seen as an advantage that the sea salt battery is able to tolerate high temperatures up to 80°C.

However, to use the sea salt battery in e-rickshaws, a BMS is required to monitor the Depth of Discharge (DoD) of the battery for operators. Interviews showed that the drivers use applications to monitor the status of their battery, to find available charging stations where there is no queue, and to route them to the charging stations (Interview Lithion Power). The need for a BMS integrated within the battery system is therefore necessary. This is an important parameter for the sea salt battery to be considered feasible as battery technology in e-rickshaws.

4.1.2 Battery Compartment Dimensions

Interviews with several battery charging stations revealed that there is sufficient space in the battery compartment, allowing batteries of different sizes to be placed in the e-rickshaws. As there are different types of e-rickshaws, the sizes for the battery compartment will differ. The e-rickshaws from ETO Motors, known for their manufacture of e-rickshaws, their provision of fleet operations and their charging infrastructure, are used in this comparison. The dimensions of the battery compartment are 59 cm in length by 38 cm in width by 30 cm in height (Interview ETO Motors). The boundary conditions concerning the available place for an e-rickshaw battery are thus subject to these dimensions. Table 3 shows different dimensions for different battery technologies.

Table 3. Comparison of batteries based on dimensions, weight, and power capacity (Ten Kortenaar et al., 2021) (Cygni Energy, 2021) (Livguard, 2022)

Battery technology	Dimensions (L x W x H)	Weight (kg)	Power capacity (kWh)
Lead-acid	41,5 x 30 x 25,2 cm	35	4,14
Lithium-ion	54,2 x 27,5 x 20 cm	35	4,08
Sea salt	56 x 36 x 16 cm	20	0,25-1

The lithium-ion and lead-acid battery were taken as examples of the possible batteries available on the market and were chosen because 4 kWh batteries are usually used in e-rickshaws (Interview EMO Motors). The lead-acid battery with dimensions 41.5 x 30 x 25.2 cm and the lithium-ion battery with dimensions 54.2 x 27.5 x 20 cm fell within the range of the battery compartment - of 59 x 38 x 30 cm (Cygni Energy, 2021) (Livguard, 2022). After research, it was seen that the sea salt battery fell within the limitations of the boundary conditions, with dimensions of 56 x 36 x 16 cm (Ten Kortenaar et al., 2021).

So technically, based on the e-rickshaw model used by ETO Motors, it is possible for the sea salt battery to be placed in an e-rickshaw. However, the sea salt is close to the limitations of the place available in the compartment, and it would therefore help if the battery were smaller. Furthermore, it was clear to see that the capacity of the sea salt battery is not currently competitive, with a capacity of 0.25-1 kWh, which is less than that of lead acid and lithium ion, with capacities of 4.14 kWh and 4.08 kWh respectively for a battery with the same dimensions (Cygni Energy, 2021) (Livguard, 2022). On the other hand, the weight of the sea salt battery is lighter, compared with the others. Regarding energy losses, lighter batteries preserve more energy compared with heavier batteries (Li et al., 2021). As the sea salt battery weighs 20 kg and is almost half the weight of each of the other two batteries, this would be an advantage. However, it is not clear whether this weight would remain unchanged if the capacity of the sea salt battery were improved. If the weight remained the same, the sea salt battery may be a competitive solution, compared with the other, heavier, batteries.

4.1.3 Conclusion

The first sub-question *How can the sea salt battery become technically feasible for electric rickshaws?* is answered as follows:

Based on the much longer cycle life, the sea salt battery outperforms commercial batteries. Although the cycle life of the sea salt battery has not been tested in the field, it can be seen as promising. Also, given the wider temperature range and dimensions suitable for placement within an e-rickshaw, the sea salt battery shows the potential to be used in e-rickshaws. Currently, one of the most important limitations for e-rickshaw operators is the range of the battery. The sea salt battery can keep up with commercial batteries, in terms of specific energy. However, as the sea salt battery has a limited capacity in terms of energy density, this currently hampers their ability to compete with commercial batteries. Thus, to improve the feasibility of the sea salt battery, more research and design optimisation needs to be done, in order to increase the energy density and thereby the range of this battery. Improvement on this technical aspect could help develop it as a feasible technology for e-rickshaws.

4.2 ECONOMIC FEASIBILITY

In this section, the economic feasibility of the sea salt battery to use in e-rickshaws is explored. To explore how the sea salt battery can be economically feasible, the battery prices of commercial technologies and their energy cost per kWh of battery storage will be mapped and compared. In addition, the different battery costs borne by e-rickshaw drivers relative to their total expenses and income are mapped out. The second sub-question *How can the sea salt battery become economically feasible for electric rickshaws?* is answered within this section by applying the methods discussed in chapter 3.

4.2.1 Comparison to other Commercial Batteries

Methods such as an internal rate of return (IRR) and a net present value (NPV) are used to indicate the profitability of a (new) technology, potential investment or project (Herriott, 2014). Anuphappharadorn et al. (2014) and Podder & Khan (2016) used these metrics to compare the lead-acid and lithium-ion battery in a photovoltaic stand-alone application system and in a solar home system. Also, Jaiswal (2017), Biggins et al. (2021) and Kebede et al. (2021) used these metrics and calculations in their techno-economic analysis where lead-acid or lithium-ion batteries were integrated in different systems. These methods will not be used during this thesis because, in the appointed literature, many components that were used in calculations are not relevant to an e-rickshaw. Moreover, due to the absence of cash flows and other independent financial data to calculate these parameters, these methods will not be used during this feasibility study.

Another method that can be used to compare different battery technologies from an economic perspective is by studying the cost per kWh of battery storage (Dhundhara et al., 2018) (Kebede et al., 2021) (Madlener & Kirmas, 2017). This is an important cost parameter for e-rickshaw operators (Tirpude et al., 2020). Battery capacity is indicated by two terms: the unit Ampere-hour (Ah) and the unit Watt-hour (Wh). The unit Ah indicates how long a battery can deliver a given current for one hour, while the unit Wh indicates how much energy it can deliver (Papiewski, 2019). Ultimately, it is not the current delivered but the energy supplied that matters when comparing batteries. Therefore, comparing batteries will be done in the units Wh or kWh. One disadvantage of this method is that the cost per kWh of battery storage is subject to developments, meaning the declared cost quickly become out of date (Armand et al., 2020) (Abas et al., 2019). An advantage is that it gives a clear picture of what economic parameters the sea salt battery must meet in order to become economically feasible as a battery technology for e-rickshaws.

Comparison on cost per kWh of battery storage

Shandilya et al. (2019) and interviews show that e-rickshaws in New Delhi normally contain four batteries with a capacity of 1 kWh or more per battery. The overall battery capacity in e-rickshaws is mostly around 4 kWh (Gode, Bieker & Bandivadekar, 2021) (Interview EMO Motors). Therefore, 1 kWh batteries were used with both technologies, to compare the economic parameters. The details and cost of the batteries used in this study are given in Table 4.

Table 4. Costs of lead-acid, lithium-ion and sea salt batteries (Dhundhara et al., 2018) (Kebede et al., 2021) (Ten Kortenaar et al., 2021) (Interview Dr.Ten)

Parameters	**Type of battery**		
	Lead-acid	**Lithium-ion**	**Sea salt**
Nominal cell voltage (V) and maximum capacity (Ah)	12 V, 83 Ah	6 V, 167 Ah	12V, 20-83 Ah
Nominal capacity (kWh)	1 kWh	1 kWh	0.25-1 kWh
Cost (€/kWh)	104-124	463-630	800-1400

Table 4 shows that the cost per kWh of battery storage for lead-acid batteries ranges between 104-124 €/kWh. For lithium-ion batteries the costs per kWh of battery storage range between 463-630 €/kWh (Dhundhara et al., 2018) (Kebede et al., 2021). Regarding Table 4, lithium-ion batteries are 3.7-6 times more expensive, when comparing it with lead-acid batteries with the same battery capacity. The same view emerged in the interviews, being said that lead-acid batteries are at least 3-4 times cheaper compared with lithium-ion batteries when taking the same battery capacity (Interview Mobilytics). The interview with ETO Motors strengthened this view, pointing out that the Indian market is known to be highly price sensitive. Studies from Tirpude et al. (2020) and interviews with charging operators showed that more than 80% - 90% of the e-rickshaw operators use lead-acid batteries for this reason (Interview Mobilytics, ETO Motors and Lithium Power).

Lead-acid batteries, due to their low cost combined with their technical properties, have the lead in the overall battery market (Diouf & Pode, 2015). Despite subsidies for the purchase of lithium-ion batteries, most operators still opt to buy the cheaper lead-acid batteries (Interview Prem, Mobilytics & Lithion Power). Therefore, the prospect of a cheaper cost per kWh of battery storage for sea salt batteries is important. Table 4 shows that the sea salt battery cost per kWh of battery storage ranges between 800-1400 €/kWh (Ten Kortenaar et al., 2021). The sea salt battery is at least 8 times more expensive than the lead-acid battery, and roughly 4 times more expensive than the lithium-ion battery. Accordingly, this shows that the sea salt battery is currently not economically competitive. However, it should be considered that the sea salt battery is still in the development stage and therefore has high production costs, while the highlighted other batteries are mass produced. Nurohmah et al. (2022) reported that large-scale production of the sea salt battery could potentiate a relatively low price for battery storage.

Comparison of battery prices on the Indian market

Currently, the Indian e-rickshaw battery market offers different battery technologies with different capacities. This section reviews the prices for lead-acid and lithium-ion batteries with capacities around 1 kWh, to get an indication of into which price range the sea salt battery should fall to compete with commercial batteries.

Table 5. Prices of lead-acid and lithium-ion batteries in the India market (IndiaMART, 2022)

Brand	**Model**	**Voltage (V)**	**Current (Ah)**	**Capacity (kWh)**	**Price (€)**	**€/ kWh**
Microtex	Lead-acid	12 V	100 Ah	1.20 kWh	€62,00	€51,66
Zen	Lead-acid	12 V	100 Ah	1.20 kWh	€86,80	€72,33
Decor	Lead-acid	12 V	105 Ah	1.26 kWh	€117,80	€93,49
Explore Synergy	Lithium-ion	48 V	24 Ah	1.15kWh	€214,27	€186,32
Eteily	Lithium-ion	60 V	15 Ah	0,9 kWh	€179,80	€199,78
JETz	Lithium-ion	48 V	40 Ah	1.92 kWh	€387,24	€201,69

Table 5 shows that, as stated in the section above, lithium-ion batteries can sometimes be 4 times more expensive compared with lead-acid batteries with the same capacity. This applies when comparing the Microtex battery with the JETz battery (IndiaMART, 2022). Furthermore, it shows that there is a big difference in terms of price per battery technology. In contrast, the price range per technology in Table 5 is cheaper compared to the price ranges found in the literature, displayed in Table 4. This can be attributed to the fact that developments are so rapid that they quickly render values in literature obsolete. Nevertheless, it should be noted that Table 5 does not include the quality and lifespan of the battery. However, it does give an indication that the sea salt battery can be economically competitive, if the price per kWh of the battery storage system falls within the same price ranges as those for lead-acid and lithium batteries, as shown in Table 4 and Table 5.

4.2.2 Battery Costs for E-Rickshaw Operators

Interviews with e-rickshaw operators discussed their income and expense pattern. These interviews provided insight into what drivers currently pay for their charging costs and how this compares with their overall expenses and income. This is important because the ratios of their charging costs to their total cost and total income provide insight into the importance of a cheaper battery with competitive energy density. This data was analyzed, to see how it could provide insight into the economic feasibility of using sea salt batteries in e-rickshaws.

Charging costs in relation to revenues

Interviews with e-rickshaw drivers provided insight into their cost structure. The outcomes of different interviews with the operators are as followed:

- When assessing the charging costs per month of e-rickshaw operator R. Singh, the average monthly expense for loading costs is IRN 6,500, while his income is between IRN 18,000-20,000. This means that he spends approximately between 32% and 36% of his monthly income on charging costs (Interview Singh).
- K. Kumar pays IRN 250 per day which ensures that he can replace as many batteries per day as needed. His average monthly expense for loading costs is IRN 7,000, while

his monthly income is on average IRN 19,000. Therefore, it can be determined that 37% of his total income per month is spend on charging costs (Interview Kumar).

- The monthly recharging fee of e-rickshaw operator Chotu averages IRN 6,200, while his income is between IRN 18,000-20,000. This means that he spends approximately between 31% and 34% of his monthly income on charging costs (Interview Chotu).

Charging costs in relation to expenses

The interviews with e-rickshaw operators also provided insights into the relationship between their charging costs and their total expenses. The outcomes of the different interviews with the operators are as follows:

- The monthly expenses of e-rickshaw operator Singh are on average IRN 9,000, while his charging expenses are on average IRN 6,500. This means that 72% of the e-rickshaw's total monthly cost is spent on charging (Interview Singh).
- Kumar pays IRN 10,000 in total expenses per month of which IRN 7,000 is spent on charging fees. This means that 70% of the e-rickshaw's total monthly cost total cost is spent on charging (Interview Kumar).
- Another e-rickshaw driver Chotu pays on average IRN 8,600 on total expenses, where IRN 6,200 is used for charging costs. This means that 72% of the e-rickshaw's total monthly cost is spent on charging (Interview Chotu).

On average, the drivers surveyed earned between IRN 18,000 and 23,000 per month. It should be noted that the income of the full-time e-rickshaw driver is not fixed and at the time of writing was and still is heavily influenced by the COVID-19 pandemic. Compared to their cost structure, the charging costs of operators are between 31-37% of their total expense. What is notable here is that of the drivers surveyed, around 70% of the total expenses are for charging costs. (Interviews Singh, Kumar, Chotu and Prem).

Different charging cost structures

Further, several types of cost structures for charging methods were discussed during these interviews. The most common were the methods of parking and charging at a charging station, or swapping the battery at a charging station. These are listed as follows:

- *Parking and charging*: In the area studied, the cost for a day of charging, including parking, averages IRN 120/day. The conversation with ETO Motors, which operates the business model for parking and charging, revealed that charging costs are between 10-12 IRN/kWh. This means that for 40-50 IRN, operators obtain a fully- charged battery again, assuming their e-rickshaw contains a 4-kWh battery. Drivers then pay IRN 150 per day, since most charge their vehicles three times a day (Interviews Singh, Chotu & Kumar)
- *Swapping stations*: Regarding swapping stations, such as Lithion Power, charging costs are based on kilometers driven. With a battery range of 60 km, the costs will be around 150 IRN per swap. Usually, the driver pays by subscription, where for 250 IRN the driver can change batteries all day. It is also possible to first pay 150 IRN for the first battery and 50 IRN for the second, if needed (Interviews Singh, Chotu, Kumar & Mohan)

It is notable that of the drivers surveyed, 80% use a battery that can be changed at a swapping station (Interviews Singh, Chotu, Kumar & Mohan). Interchangeable batteries eliminate the inconvenience of proprietary batteries and high start-up costs. Finally, drivers no longer have to go to a base location every day to charge their vehicles necessitating long waiting times for recharging. This makes them more flexible and thus more employable in different parts of the city (Ahmad et al., 2020). However, setting up a battery swapping station is very capital intensive. It requires more than twice as many batteries as there are in operation, as a reserve to replace empty batteries (Interview Mobilytics). However, if there are more swapping stations, e-rickshaw drivers would benefit as it would allow them to swap batteries at even more locations.

4.2.3 Conclusion

In section 4.2 it was determined that the sea salt battery is currently too expensive, compared with commercial batteries, and therefore not yet economically competitive. Because the sea salt battery is still in the development stage, and not yet mass-produced, production costs are still high. Lead-acid batteries are now the most widely-used batteries because of their cheaper price and competitive energy density. However, developments have been shown to be rapid, causing costs per kWh of battery storage to change rapidly. The analysis showed that the

Indian battery market is very price sensitive, which highlights the importance that the salt battery could compete, in cost, with lead-acid batteries.

This analysis has shown that the charging costs of e-rickshaw operators accounted for, on average, one-third of their total expenses. Furthermore, around 70% of their total expenses are for charging costs. It can be observed that most of their costs are allocated to charging activities, providing insight into the importance of a cheaper battery that can deliver high mileage. Consequently, the vast majority of drivers use swapping stations, because it allowed them to make more trips and earn more money, depending on when they charge and park their e-rickshaw vehicle. These operators earn more revenue because they can easily replace their battery instead of having to wait while charging. This is an interesting development in the world of e-rickshaws and could be a promising business case for the sea salt battery.

4.3 SOCIAL FEASIBILITY

This section explores the social feasibility of using the sea salt battery in e-rickshaws. During this analysis, the battery safety and environmental parameters of commercial batteries and the sea salt battery were analyzed and compared. The third sub-question *How can the sea salt battery become socially feasible for electric rickshaws?* is answered within this section by applying the methods discussed in chapter 3.

4.3.1 Battery Safety

Battery safety issues are a public concern and therefore important when assessing the feasibility of a new battery technology (Tang et al., 2019) (Huang et al., 2021) (Lisbona & Snee, 2011). Therefore, the safety characteristics of the sea salt battery were explored and compared with those of lead-acid and lithium-ion batteries. Table 6 gives an overview of the main characteristics that will be covered in this section regarding the safety aspects of the different batteries.

Table 6. Comparison of batteries based on different literature and interviews (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021) (Interview Dr. Ten)

	Lead-acid	Lithium-ion	Sea salt
Safety requirements	Thermally stable	Protection circuit needed	Thermally stable
Maintenance requirements	3-6 months	No requirements	No requirements
Toxicity	Very high	Low	Very low

Comparison of safety requirements

Table 6 shows that, regarding the three compared batteries, lithium-ion batteries have the highest risk of a thermal runaway and need therefore a protection circuit, also known as a BMS (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021). Lithium-ion batteries contain a number of hazardous components, which are highly flammable solutions (Lisbona & Snee, 2011). The risks of defects or errors when in operation are present, which can lead to thermal runaway, over-pressurization, fire and/or explosion of battery packs (Zhang et al., 2016). In comparison, lead-acid and sea salt batteries are thermally stable and therefore do not have the risk of a thermal runaway and explosion of the battery packs (Zhang et al., 2016) (Lisbona & Snee, 2011) (Albright, Edie, & Al-Hallaj, 2012) (Lee et al., 2021). This might then speak in the sea salt battery's favor, when considering the social acceptance of battery technologies.

Comparison of maintenance requirements

When comparing the batteries, regarding maintenance requirements, as shown in Table 6, it can be seen that only the lead-acid battery is subject to this (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021). In lead-acid batteries, multiple ageing processes take place, which lead to a gradual loss of performance, and eventually to the end of service life (Albright, Edie, & Al-Hallaj, 2012) (Diouf & Pode, 2015) (Ruetschi, 2004) (Chang et al., 2009). To counteract this, clean distilled water needs to be added to lead-acid batteries every three to six months. In contrast, new lead-acid technology batteries, such as valve-regulated lead-acid (VRLA), do not have to be maintained with the addition of distilled water during service life, making them maintenance-free (Lambert, Greenwood, & Reed, 2002). In terms of maintenance, none of the three batteries is inferior to another, when used correctly.

Comparison on toxicity levels

Table 6 shows that the toxicity level of lead-acid batteries is very high (Diouf & Pode, 2015) (Lee et al., 2021). As stated in section 2.2.1, it is known that substances inside the lead-acid battery are very toxic for humans and the environment (Gottesfeld et al., 2018) (Chen et al., 2012). These substances do not pose a problem during battery use. However, they do if these substances are released into the environment when the batteries reach the end of their service life and are not properly recycled. Table 6 also shows that, in proportion to other battery technologies, the toxicity level of lithium-ion batteries is low is (Diouf & Pode, 2015) (Lee et al., 2021) (Ten Kortenaar et al., 2021). However, as stated in section 2.2.2, proper handling and recycling of lithium-ion batteries is needed to reduce pollution by metals such as cobalt, nickel and lithium, because of their toxicity to humans and nature. (Yang et al, 2021). Finally, Table 6 shows that the toxicity level of the sea salt battery is very low. In contrast to the lead-acid and lithium-ion batteries, the toxicity level of sea salt battery is very low, due to the absence of highly toxic compounds, such as strong acid and heavy metals (Ten Kortenaar et al., 2021) (Interview Dr Ten). This can be explained by the fact that sea salt batteries make use of sea salts as electrolytes and natural electrode materials (Ten Kortenaar et al., 2021). Thus, when evaluating the safety aspects of the highlighted batteries, the sea salt battery appears to be the best choice for both humans and the environment.

4.3.2 Environmental impact

The production method and the recycling potential are important parameters, as these determine to what extent a battery technology can be considered an environmentally friendly energy carrier (Hawkins et al. 2012). Due to the fact that there is still little literature on the environmental impact of the production and recycling of sea salt batteries, the literature on the life cycle assessments of the lead-acid and lithium-ion battery was reviewed (Peters and Weil (2018) (Yudhistira, Khatiwada & Sanchez, 2022). To compare the environmental impact between batteries, the environmental parameters of competing batteries were analyzed. Then, a benchmark was created, which served as a reference with which the sea salt battery could be compared to review how competitive it was, in terms of sustainability.

Acidification Potential and Global Warming Potential

One way to compare different battery types based on their impact on the environment is to look at sustainability parameters. Parameters such as the acidification potential (AP) and the global warming potential (GWP) are used to measure the impact of a battery on the environment (Dincer and Acar, 2015). Many researchers, such as Cabrera (2013), Peters & Weil (2018), Yudhistira, Khatiwada, & Sanchez (2022), have mainly focused on GWP and AP as the parameters for environmental impact analysis. Since the literature values for GWP and AP are available, this section will focus solely on these two parameters.

In the life cycle assessment of EVs, several environmental impacts are often studied, including climate change, resource depletion, and human toxicity (Cabrera, 2013) (Peters & Weil, 2018) (Yudhistira, Khatiwada, & Sanchez, 2022). The GWP, expressed in kilograms of carbon dioxide equivalent (kg CO2 eq.), is the most widely used environmental indicator because of its simplicity and general understanding of the impact (Hawkins et al. 2012). The GWP is a relative measure that indicates the global warming potential of a greenhouse gas compared with that of carbon dioxide (CO2). In addition, AP is a widely used parameter. The acidification potential is described as the ability of certain substances to build and release H+ions and is given these equivalents (Impact Assessment Categories, 2021). After GWP, AP is the most frequently reported result (Hawkins et al. 2012). Acidification potential relates to the discarding of acidifying pollutants in surface waters, ground water, soil and ecosystems, affecting the natural environment and human health. Ozbilen et al. (2013) state that sulfur dioxide and nitrogen oxide emissions are the major contributors for AP.

Comparison of environmental impacts based on Life Cycle Analysis

Yudhistira, Khatiwada, & Sanchez (2022) performed a life cycle analysis based on several sources, aiming to evaluate the environmental impacts of lithium-ion batteries and lead-acid batteries. Their GWP and AP results are presented as shown in the Table 7.

Table 7. Environmental impacts of lithium-ion and lead-acid batteries, levelized to the lead-acid battery (functional unit is per kWh energy delivered) (Yudhistira, Khatiwada, & Sanchez, 2022).

	LFP	**NMC**	**NCA**	**Lead-acid**
Global warming potential (kg CO_{2eq})	1.64 (82%)	1.22 (61%)	1.1 (55%)	2 (100%)
Acidification potential (mol H_{+eq})	0.0202 (101%)	0.0066 (33%)	0.0124 (62%)	0.02 (100%)

Note:
LFP standing for Lithium Iron Phosphate
NMC standing for Lithium Nickel Manganese Cobalt Oxide
NCA standing for Lithium Nickel Cobalt Aluminum Oxide

Table 7 summarizes the overview of the environmental impacts of different types of batteries from cradle to grave. First, the study finds that the lead-acid battery has approximate environmental impact values (per kWh energy delivered): 2 kg CO2eq for the global warming potential and 0.02 mol H + eq for the acidification potential (Yudhistira, Khatiwada, & Sanchez, 2022). The lead-acid battery was taken as a benchmark here and is therefore indexed at 100%. From the results, it can be seen that lead-acid batteries do not fare as well as lithium-ion batteries in terms of their impacts on climate change and resource use (fossils, minerals and metals). When lead-acid is compared to lithium-ion, it appears that only 55%, 61% and 82% of the lead-acid values are determined in terms of kg CO2 equivalent for lithium-ion batteries (Yudhistira, Khatiwada & Sanchez, 2022). When assessing the AP, lead-acid batteries have a greater effect on the acidification potential (except for the LFP chemistry). The main reasons for these differences are that lithium-ion has a higher energy density and a longer lifespan. As a result, lithium-ion batteries require fewer battery cells for the same energy requirements as lead-acid batteries, resulting in a lower environmental impact, regarding the GWP and AP (Yudhistira, Khatiwada & Sanchez, 2022).

It is challenging to compare the results of the life cycle assessment of Yudhistira, Khatiwada, & Sanchez (2022) with alternative literature and studies, due to the different system boundaries and methodology. However, the results can be compared with the study by Peters and Weil (2018) because it is used as inventory data and is the primary source to determine the carbon impact of a product from the moment it is produced to the moment it enters the store. Table 8 shows the comparison between the results of both studies for the GWP and the AP. The results obtained are described in terms of percentages of the literature values.

Table 8. Comparison of the life cycle analysis impacts between Peters and Weil (2018) and Yudhistira, Khatiwada & Sanchez (2022).

Impact Category/Battery type		**Global Warming Potential (kg CO2eq)**	**Acidification (mol H + $_{eq}$)**
LFP	Literature	169	2.33
	Obtained	100%	82%
NMC	Literature	104	1.04
	Obtained	139%	106%
NCA	Literature	115	5.1
	Obtained	99%	35%

Note: Peters and Weil (2018) are used as literature reference, while the study by Yudhistira, Khatiwada & Sanchez (2022) is used here as obtained values.

Other than the 65% difference between the literature and obtained results for the acidification potential of NCA battery packs, the other values do not differ much from each other (Yudhistira, Khatiwada & Sanchez, 2022) (Peters & Weil, 2018). Therefore, the study by Yudhistira, Khatiwada, & Sanchez (2022) can be adopted as a reliable source during this environmental analysis.

It can be seen that the acidification potential and the global warming potential of lead-acid batteries are greater than those of lithium-ion batteries (Yudhistira, Khatiwada & Sanchez, 2022) (Peters & Weil, 2018). Thus, it can be said that the sea salt battery would be competitive in terms of environmental impact, if the GWP of the sea salt battery could be below 1.1 CO2 per kWh of energy delivered and the acidification potential below 0.0066 H+ per kWh of energy delivered, considering those being the lowest values (Yudhistira, Khatiwada & Sanchez, 2022) (Peters & Weil, 2018). With lower CO2 and H+ emissions than lead-acid and lithium-ion batteries, the sea salt battery would be more environmentally friendly. Since the sea salt battery consists of local sea salt, minerals and graphite, this could be feasible. However, this must be confirmed by subjecting the sea salt battery to laboratory analyses.

4.3.3 Conclusion

In this section, the third sub-question *How can the sea salt battery become socially feasible for electric rickshaws?* is answered as follows:

It speaks in the favor of sea salt batteries that they are thermally stable, which contributes positively to the social acceptance of the sea salt battery, in contrast to the lithium-ion battery. Moreover, there is no maintenance required for the battery. This, however, does not differ from other commercial batteries. From a safety perspective, on the other hand, the sea salt battery seems to stand out. The sea salt battery has high chances of scoring better than commercial batteries in terms of sustainability. However, comparative research is needed to confirm this.

Research shows that lead-acid batteries do not fare as well as lithium-ion batteries in terms of climate change impacts. Thus, to be socially viable as a sea salt battery, it is at least necessary to outperform lead-acid batteries on this aspect. Since the sea salt battery consists of local sea salt, minerals and graphite, this may be feasible. Although this needs to be confirmed by lab research. This could be achieved by with lower CO_2 and H^+ emissions in compared with lead-acid and lithium-ion batteries.

5. CONCLUSION AND DISCUSSION

In this thesis, the feasibility was explored of how the sea salt battery could become a feasible technology for e-rickshaws in New Delhi, India. This chapter will conclude the research by answering the sub-questions and main research question, based on the results of the study. Next, limitations of this study will be discussed. Lastly, recommendations will be proposed.

5.1 CONCLUSION

This section will present the conclusions of the thesis research by answering the research questions. The sub-research questions will be answered first, followed by the answers to the main question.

The first sub-question *How can the sea salt battery become technically feasible for electric rickshaws?* is answered as follows:

Over the years, only a select group of batteries have been used in e-rickshaws. The technical parameters of these battery technologies play an essential role in this particular. The results of the case study were consistent with the literature review, which showed that energy density, and thus range, is one of the most important parameters for evaluating e-rickshaw batteries. It can be stated that the sea salt battery currently underperforms, in terms of energy density, compared to commercial battery technologies. So, by improving the energy density to at least the same values as those of commercial batteries, the sea salt battery could potentially become a feasible technology for e-rickshaws. In contrast, the sea salt battery showed positive results in other technical aspects. The study showed that the sea salt battery outperformed commercial batteries, in terms of cycle life. More simulations and lab research need to be done on this, but this could potentially save drivers a lot of costs, if they have to buy a new battery much less frequently. In addition, it was found that the sea salt battery is suitable to be placed in an e-rickshaw. Furthermore, outcomes of the case study showed that it is desirable to integrate the sea salt battery with a BMS system, which facilitates and improves the operations of the e-rickshaw operators.

The second sub-question *How can the sea salt battery become economically feasible for electric rickshaws?* is answered as follows:

The literature and case study showed that the Indian battery market is highly price sensitive, which makes a low energy cost per kWh of battery storage important. Regarding this aspect, it was determined that the sea salt battery is currently too expensive, compared with commercial batteries, and therefore not yet economically competitive. The fact that the sea salt battery is currently in its development stage, thus incurring high production costs plays a major factor in this. Therefore, lower costs per kWh of battery storage should be achieved by the sea salt battery, in order to become more feasible for use in e-rickshaws. Moreover, the importance of low-cost battery storage was strengthened by findings that showed that around 70% of the total expenses - equating to one-third of the revenues - of drivers are spent on charging costs. Consequently, to waste less time recharging their batteries, the case study found that the vast majority of e-rickshaw drivers use replaceable batteries that can be changed daily. This allows them to resume work quickly, make more trips and earn more money. Thus, it could be an interesting business case to make the sea salt battery suitable for operations with swapping stations.

The third sub-question *How can the sea salt battery become socially feasible for electric rickshaws?* is answered as follows:

Due to the very low toxicity of the sea salt battery, compared with its competitors, the sea salt battery performs very positively in terms of social acceptance. Additionally, it is favorable that the sea salt battery requires no maintenance, and its thermally stability would prevent dangerous situations such as explosions. All this contributes positively to the feasibility of using the sea salt battery for electric rickshaws. Nevertheless, these findings are based on literature and therefore need to be validated by specific research, including the toxicity of the sea salt battery. Regarding the environmental impact of other batteries, the acidification and global warming potential of lead-acid batteries have both been shown to be greater, and thus worse, for the environment compared to lithium-ion batteries. This comparison created a benchmark from which the sea salt battery must perform better to emit fewer emissions. Because the sea salt battery consists mainly of local sea salt, minerals and graphite, the sea salt battery is expected to perform better in terms of acidification and global warming. However, because the study of these potentials was exploratory and no life cycle analysis of the sea salt battery was conducted, further research is needed to validate expectations regarding environmental parameters.

By combining the findings of the sub-questions answered throughout this thesis, the main research question ***How can the sea salt battery become a feasible technology for electric rickshaws in New Delhi, India?*** is answered as follows:

This study showed that sea salt batteries are feasible to be used in e-rickshaws if the energy density and cost per kWh of battery storage are improved and come close to that of commercial batteries. The importance of this was reinforced after it was revealed that 70% of drivers' total spending goes on charging costs. Therefore, to reduce the time spent waiting while charging, the majority of e-rickshaw operators are increasingly using replaceable batteries. Hence, it could be interesting to make the sea salt battery suitable for operations with swapping stations. With its environmentally friendly battery materials and safe battery chemicals, the sea salt battery has a strong value proposition over commercial batteries in terms of social acceptance. Along with its longevity and better performance in hot climates, the sea salt battery may hold promise for e-rickshaw drivers in India if it manages to improve energy density and lower the cost per kWh of battery storage.

5.2 LIMITATIONS OF THE STUDY

This thesis is subject to several limitations, due to the research scope and the research methodology.

5.2.1 Research Scope

This thesis researched the feasibility of the sea salt battery as a technology for electric rickshaws in New Delhi, India. The study was based on technical, economic and social feasibility. However, the inclusion of these three aspects proved to be a lot and the research would have had more focus if it could have just focused on technical and economic feasibility. A limitation of the study is because it examined three aspects broadly, sometimes lacking some depth that could have strengthened the study. The exclusion of the social feasibility aspect could have provided more perspectives on the technical and economic feasibility, and therefore enhanced the depth of the results. Another limitation of this research was that for a long time the author was unable to clearly define the scope of the study. As a result, time and energy were lost in changing the focus of the study.

5.2.2 Research Methodology

For data collection, a desk study was conducted, in combination with a single case study method. Due to the limited amount of research published regarding the sea salt battery, the data collection for the sea salt battery was largely based on the information provided by Dr. Ten. Subsequently, another limitation of this study is the lack of conducting own research, to obtain more data on sea salt batteries. More research and experiments on the technical, economic and social parameters of the sea salt battery should have been done to combine with the desk study, to draw better conclusions about the feasibility of the sea salt battery. Now, a limitation of this study is that conclusions are drawn about technical, economic and social components of the sea salt battery, without the author's back testing of found parameters in literature and doing additional research. Since the parameters used were not independently examined, it can be argued that this compromises the reliability and validity of the study.

Moreover, it should be kept in mind that this study was conducted during the COVID-19 epidemic. Due to the pandemic, it was not possible to conduct the interviews in person in India for a certain period of time. As a result, fewer interviews were conducted, which affected the validity and reliability of the study. The interviews with e-rickshaw operators were conducted through an intermediary, which prevented the author himself from continuing to ask questions. Accordingly, a drawback was that the author could not make adjustments during the interview when certain questions did not receive clear or useful answers. It would have helped if the author himself had gone to India to conduct the interviews or had been more involved with the intermediary conducting the interviews. This could have been done by being in live communication with the intermediary to listen in on the interviewee's answers. This would have allowed the author to make adjustments if the interviewee's answers were not sufficient. Thus, a limitation of this study is that the author was not physically present in India and did not have close contact with the intermediary when the interviews were conducted. Another consequence of the author's absence in the interviews with e-rickshaw operators, was that it was not noticed in time that some parts of the interviews were not useful and therefore more interviewers were needed. Therefore, another limitation of this thesis is that a larger group of respondents for e-rickshaw operators and other stakeholders would have been desirable. This could have led to more useful results.

The author deliberately chose a semi-structured interview beforehand because it allowed for input from the interviewer, allowing topics to be raised that the author might not have considered. However, the interviews conducted often led to short, inaccurate answers. This can be attributed to the questions asked by the author, which, after analyzing the interviews, were not well enough formulated or delineated. Had the questions been asked more sharply, better answers would have come out. This was quite noticeable in the interviews for the social feasibility analysis. Because here questions were not formulated clearly enough or were not even asked, this caused problems in the analysis of these. Therefore, for follow-up research, a more structured and clearer questionnaire should be used, which can lead to clearer and more useful answers, from which more information can be derived. This study revealed that framing the e-rickshaw driver and other stakeholders in India is a complex task. In conducting the interviews, social and cultural aspects were found to be largely relevant in obtaining good interview results. Understanding this relationship proved to be important in conducting and assessing the feasibility analyses.

A feasibility analysis was conducted for the data analysis. Based on the interviews and published data, assumptions were made to make statements about how the sea salt battery might become feasible for e-rickshaws. In cases where a lot of uncertainty is involved, it was difficult to convert qualitative information into quantitative assumptions. This was the case, for example, in the economic and social feasibility analysis. Some assumptions are highly uncertain, making the results of the study less reliable. For example, the economic feasibility analyses were only based on a few useful interviews with e-rickshaw operators, while the interviews for the social analysis were rejected due to poor questioning and therefore bad performance of the interviews. Due to the lack of usable survey results, the influence of institutions, culture and government could not be tested unambiguously, as the author had envisioned at the beginning of the study. As a result, it was decided to exclude this section from the social feasibility analysis.

Another limitation of this study is that the feasibility analysis did not use methods commonly used in the literature. For example, HOMER software, a software application that allows technical and financial design and evaluation of battery technology options, is commonly used (Nair et al., 2010) (Amutha & Rajini, 2016) (Halabi et al., 2017). The use of this software was beyond the scope of this thesis because more specific data was needed while this thesis focused on exploratory research. However, using this software might have made it an option to simulate a sea salt battery system integrated into an e-rickshaw, and thus find out important boundary conditions. In addition, economic feasibility analyses typically use methods from Herriott (2014) to calculate and compare various economic parameters, such as internal rate of return on investment (IRR), net present value (NPV) and net cost of production (NPC) over the life of the technology (Siddique et al., 2014) (Rotella et al., 2021) (Jumare, 2020). Calculating such parameters for the sea salt battery has not been done, but could have enriched this thesis as it provides more interpretation and comparison compared to other commercial batteries. Finally, a commonly used method to analyze social feasibility is by conducting a life cycle assessment of a battery (Cabrera, 2013) (Peters & Weil, 2018) (Yudhistira, Khatiwada, & Sanchez, 2022). Literature regarding these life cycle assessments have been used to compare the GWP and AP as the parameters for environmental impact analysis. However, a limitation of this research is that during this thesis conducting such an assessment was not done for the sea salt battery, while this could have validated the battery's stated benefits in terms of more sustainable and safer battery.

5.3 RECOMMENDATIONS

Now that the findings of the thesis work have been discussed and conclusions drawn from them, several practical implications will be discussed. Furthermore, recommendations will be made for the future expansion of this work.

5.3.1 Practical Implications

The recommendations for the involved actors following from the implications are summarized in this section.

Dr Ten

The study found that Dr. Ten should aim to increase the energy density of the battery. Therefore, it is recommended to research the chemistry of the battery more intensively to gain improvement in this area. Furthermore, it was also appointed that lowering the costs per kWh of battery storage is necessary to be competitive compared with commercial batteries. However, there is no need to focus on this first, since the cost per kWh of battery storage will gradually become cheaper the moment Dr. Ten decides to go into mass production.

Another recommendation for Dr. Ten is to use the sea salt battery more in pilot projects, with the goal of generating more data how the sea salt battery performs in an e-rickshaw. This is important for the further development of the battery, as not much data is currently available for the sea salt battery in operation. Because the sea salt battery is socially beneficial because of its safety and low environmental impact, it can help get pilot projects off the ground in cooperation with municipalities and the government of India. Establishing charging projects with the sea salt battery also aligns well with the goals of the Government of India, which through the FAME India Scheme and The National Mission for Transformative Mobility and Battery Storage aims to encourage the construction of charging infrastructure to support electric vehicles of all categories (Government of India, 2019) (The Economic Times, 2019).

Besides focusing on e-rickshaws, with such a battery life, the sea salt battery could also be used for other purposes. The sea salt battery could potentially serve as a stationary storage device that stores power through solar panels. Unlike lead-acid and lithium batteries, the sea salt battery could be used for outdoor devices because the battery does not require cooling and maintenance. Consequently, the sea salt battery could be placed behind solar panels, potentially saving on electronics, cooling costs, complexity and maintenance costs compared with commercial batteries. Rickshaw drivers and other EV users could then charge their batteries via this stationary sea salt battery. This could be relevant for both on-grid and off-grid applications. Therefore, it is recommended to further focus on these applications as the sea salt battery outperforms commercial batteries in this regard.

Municipalities and national government

The reliance on relatively expensive, scarce and non-renewable materials will only increase if no renewable alternative enters the market as a competitor (Sovacool, 2019). This study highlighted the importance and need for sustainable battery technologies that will have to replace commercial batteries during the energy transition to renewable energy sources. The adoption of these sustainable battery technologies desperately needs the support of municipalities and the national government. Therefore, it is recommended that the municipality and government participate more actively in the battery market by providing subsidies to manufacturers of renewable batteries and increasing taxes for manufacturers of non-renewable batteries. This will affect the cost price of batteries, making sustainable batteries attractive to e-rickshaw operators in the long run, who mainly buy the cheapest batteries.

It is also recommended that municipalities provide subsidies to e-rickshaw drivers who use or purchase a sustainable battery. Here, it is important that the government closely monitor that municipalities provide these subsidies. This would only strengthen the demand for sustainable batteries, something that is also desirable for municipalities and governments in the long run. Currently, people in India receive a grant when they purchase an e-rickshaw, but the case study revealed that a number of e-rickshaw operators interviewed were not aware of this. Thus, it is important to counteract the information asymmetry that currently exists. Therefore, it is recommended that the government and municipalities establish better information facilities for e-rickshaw drivers to make them aware of the available schemes and benefits of purchasing a renewable battery e-rickshaw. In addition, it is important that municipalities and governments make efforts to increase operator awareness by making clearer the disadvantages of currently commercially used batteries and the positive characteristics and externalities of the sea salt battery. This will potentially contribute to operators choosing the currently more expensive renewable battery.

E-rickshaw operators

This study showed that the sea salt battery can potentially have a much longer lifetime than commercial batteries. Only if the sea salt battery manages to become competitive in terms of energy density and cost per kWh of battery storage, this longer cycle life be beneficial to e-rickshaw operators. Operators now choose a battery that is often inexpensive despite its shorter lifespan compared to other alternatives. Thus, to achieve adoption of the sea salt battery by e-rickshaw operators, support is needed from municipalities and the government to make this battery affordable to purchase. Here, it is important that e-rickshaw operators are supported by municipalities by making them aware of the schemes if any. In doing so, it is also important that operators are clearly informed of the benefits.

5.3.2 Suggestions for Future Research

This thesis aimed to explore the feasibility of the sea salt battery technology for electric rickshaws in New Delhi, India. The following suggestions have been made for future research.

Recommendations for researching the technical feasibility

- The study found that the current energy density of the sea salt batteries is not yet sufficient to serve as a battery technology for e-rickshaws. Considering the significance of this parameter, it is of great importance to further research and improve the energy density by focusing on the chemical properties of the battery.
- It is recommended to validate the advantages of the sea salt battery, such as its longer cycle life and performing at a wider temperature range. Extensive research could be done with laboratory tests and pilot projects.
- Discussions with ETO Motors and Lithium Power revealed that in addition to battery range, charging time is one of the most important parameters for an e-rickshaw's battery. Therefore, it is recommended to conduct future research on how the sea salt battery performs while being used as energy carrier inside the e-rickshaw. In this way, the charging and discharging behavior could be tested, which is relevant when comparing the sea salt battery with commercial batteries.

Recommendations for researching the economic feasibility

- In the literature review, it was shown that methods such as the internal rate of return (IRR), the net present value (NPV) and the net production costs (NPC) are used in economic analysis over the technology’s lifetime (Siddique et al., 2014) (Rotella et al., 2021) (Jumare, 2020). For further research, it is recommended to conduct an economic evaluation of the sea salt battery, where the profitability of this new technology better could be determined (Herriott, 2014).

- The economic feasibility analysis highlighted the frequent use of swapping stations by e-rickshaw operators. Therefore, it would be worthwhile for future research to analyze the economic feasibility and payback period of this model to be used for the sea salt battery (Pattnaik & Ray, 2021) (Ray et al. (2020).

Recommendations for researching the social feasibility

- Many researchers, such as Cabrera (2013), Peters & Weil (2018), Yudhistira, Khatiwada, & Sanchez (2022), have mainly focused on GWP and AP as the parameters for environmental impact analysis. Since no literature values for GWP and AP were available for the sea salt battery, this social feasibility study used the life cycle assessments of lead-acid and lithium-ion battery as a comparison. Therefore, it is recommended to conduct a life cycle assessment of the sea salt battery. In addition, this may also validate the conclusion of this thesis - that the sustainable materials used in the sea salt battery could actually provide a competitive advantage in the Indian battery market.
- The social feasibility currently only considers environmental friendliness and safety. However, the relevance of the comprehensive background of governance, institutional conditions, and cultural values in individual enterprises is a commonly overlooked angle of approach (Kroesen, 2020). Understanding this relationship is crucial in assessing the implementation of a business proposal (Kroesen, 2020). Therefore, to strengthen the social feasibility analysis, it is recommended to research the role of culture and institutions in India, when applying a Western entrepreneurship model in the Indian society.
- Clearly, e-rickshaw drivers are playing an important role in the adoption of new battery technologies. Therefore, it is recommended that future research place more emphasis on this actor by conducting interviews that provide more say insight about the social status, knowledge and health of e-rickshaw drivers. These all play into the background and are important motivations for e-rickshaw drivers when they make choices.

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Appendix A: Interview Questions

Dr. Ten

General

- What are the disadvantages compared to other batteries?
- What problem does the sea salt battery solve (value proposition) versus other batteries?
- What are the main hurdles in the development of this battery?
- Who are your partners in developing this battery?
- What is currently keeping you from mass production?

Technical

- Have you evaluated the feasibility of producing the product?
- Have you measured how the product will perform?
- Do you have a design for the product?
- Do you have a design for the production process?
- What are the technical parameters from the sea salt battery: how does the battery work and what are the specifications of the battery?
- Could the battery be used at charging stations?
- Is the battery suitable to integrate in e-rickshaws as a 'battery swapping system'?
- Which partners play a role in the development of the battery?
- Advantages and disadvantages compared to other batteries?
- When is the battery cost effective and what needs to be done to make it so?
- Cost per kWh, energy density, kWh per one charge, how many kWh necessary to charge battery, how many kWh produced with discharge
- How does the sea salt battery work?
- What materials (minerals, carbon, salts) does the sea salt battery consist of?
- Where can these materials be obtained/found from?
- What are the technical parameters of the sea salt battery?
- Suitable for swapping for e-rickshaw? What are the barriers?
- What is the experience of using battery as charging station?
- What specification does charging station need to see if sea salt battery is feasible?
- How can they be made applicable for e-rickshaws?
- What could be a problem if these batteries are used for e-rickshaws?
- Are the batteries difficult to transport?
- Is it possible to make battery smaller?

Economical

- What are the economic parameters of sea salt battery
- When is the battery cost effective?
- Life time costs
- Is the battery cost effective? If not, when is it? How can this be achieved?
- Where does the production take place? Import/export materials?
- Who are your partners and how can they help scaling this project?

- Forecast price development for batteries over the years -> only available for tuk tuks in 10 years

Rickshaw drivers

Technical

- What are the biggest pains and barriers regarding the handling of your battery?
- Which battery technology do you use and why? (quality/price: short term-cheap, long term-expensive)
- What are the battery specifications of your battery? (if possible, metrics like battery manufacturer, lithium-ion/lead-acid, capacity,)
- What is the average lifespan of the battery you are using?
- How many times per day are you charging your e-rickshaw?
- How long does it take to fully charge an empty battery?
- What charging method (parking and charging/swapping/private charging) do you use the most and why?
- Are there enough places to charge your rickshaw?
- What is the range of a full battery, in hours and kilometers?
- How do you take care of your old battery when you decide to buy a new one?
- What will make rickshaw drivers to switch to a new battery technology? What are the drivers and barriers for this?

Economical

- What are the costs of buying a lead-acid/lithium-ion battery for e-rickshaws?
- When you buy a new battery, where do you buy this battery and why? Are those certified manufacturers?
- Do you own your e-rickshaw, or do you rent it? If renting, what are the costs per month for this?
- What is the general fee that a customer pays per distance/time?
- What are the average expenses of a full-time e-rickshaw driver per month?
- What are the average costs of charging an e-rickshaw per month?
- What percentage of your expenses goes to charging stations?
- Did you use a loan or are you receiving subsidies for your company? How did you obtain them?
- What are the revenues of a full-time e-rickshaw operator per month?
- What are the opportunities do you see to enhance your profits, regarding the charging of your battery?

Social

- Could you give some examples how the Indian government is influencing your
- business practices? Does this have a positive effect or a negative effect?
- Do you have relations with organizations that help you with your business, other than the suppliers, distributors and maybe competitors?
- If you need something from someone in your social network, how would you approach such a person (or company)?

- Sometimes you might need the help of someone you do not know or who is not in your network of friends and family. How would you approach this person (calling, email, visiting, through people you know?)
- What kind of direct contacts and interactions does your company have with governments and other organizations?
- Do these organizations impose rules and guidelines for you company? Are these rules and guidelines aimed at certain aspects (products, safety, employees, etc.)?
- How are these rules and guidelines checked and enforced?

Rickshaw manufacturers

Technical

- What technical aspects should be considered when installing a battery into an e-rickshaw? (dimensions, weight etc.)
- Looking at lead-acid/lithium-ion/NiCad batteries, on which aspects do they differ the most when placing them into an e-rickshaw?
- Which batteries do you use the most and why? What are the technical properties of these? (energy density, capacity, efficiency, voltage, discharge rate, costs per kWh)
- Which battery manufactures are you working the most with and why?
- What technical requirements must a battery (manufacturer) meet to include it in your product range?
- What are the drivers and barriers for you and rickshaw drivers to switch to a new battery technology?

Economical

- What is the average price or price range that battery manufacturers charge for a competitive battery?
- At what cost per kWh is a specific battery technology interesting for you?
- What is the order of magnitude (number of batteries) when you purchase a battery from a battery manufacturer?
- Which e-rickshaws with which battery are you selling the most and why?

Social

- What does the structure of your company look like, in terms of managers, employees and business units?
- Are there certain groupings visible in your company, in terms of ethnical background?
- How do your employees solve problems themselves?
- Are your employees trained? Which trainings have they followed?
- How do you ensure that employees handle items neatly? Or does that happen automatically?
- Who makes sure employees follow the planning?
- Do you have a lot of competition?
- Do you sometime collaborate with other actors in the sector?
- Could you give some examples how the Indian government is influencing your
- business practices? Does this have a positive effect or a negative effect?
- How are these rules and guidelines checked and enforced?

Charging stations

Technical

- What are the biggest pains and barriers regarding the charging of rickshaws during business operations? And why?
- How does the specifications of the battery limit the kind of operations?
- Is it possible to charge different kind of batteries in e-rickshaws?
- What are potential safety and environmental hazards during business operations?
- Which battery do you see the most and why? How long will this battery last?
- How many times per day are drivers charging their e-rickshaw?
- What is the average lifespan of a rickshaw battery?
- How can battery management be improved by the way of charging method so that the lifespan of these of rickshaws batteries can be expanded?
- How to deal with a battery that is no longer good? Will it be recycled?

Economical

- What are the costs per charge for an e-rickshaw driver?
- What are the charging costs for a fulltime e-rickshaw driver per day?
- What are the revenues per month of the operation of this charging station?
- Do you have competitors who differ in the pricing of their charging?
- What are the costs hiring a guard to facilitate the charging at day and nighttime?

Social

- Could you give some examples how the Indian government is influencing your business practices? Does this have a positive effect or a negative effect?
- Do you have relations with organizations that help you with your business, other than the suppliers, distributors and maybe competitors?
- If you need something from someone in your social network, how would you approach such a person (or company)?
- Sometimes you might need the help of someone you don't know or who is not in your network of friends and family. How would you approach this person (calling, email, visiting, through people you know?)
- What kind of direct contacts and interactions does your company have with governments and other organizations?
- Do these organizations impose rules and guidelines for you company? Are these rules and guidelines aimed at certain aspects (products, safety, employees, etc.)?
- How are these rules and guidelines checked and enforced?

University and Municipality of New Delhi

Technical

- What are the business operations with respect to e-rickshaws you are conducting daily? How does these key activities look like?
- What are the biggest pains and barriers regarding the charging of rickshaws during business operations?
- What are biggest trends nowadays regarding the charging of e-rickshaws? (most used batteries, new laws, subsidies which are important)

- Which barriers make it difficult to ramp up the infrastructure for charging stations for e-rickshaws?

Economical

- Are there subsidies that make it attractive for e-rickshaw operators and enterprises to perform their services?
- Is there awareness for these subsidies and how are these communicated?
- Which subsidies play at this moment a dominant role in the e-rickshaw domain?

Social

- Could you give some examples how the university/municipality is influencing the business practices of e-rickshaw enterprises?
- What kind of direct contacts and interactions does the university/municipality have with e-rickshaw enterprises and other organizations?
- How is the government influencing the e-rickshaw domain at this moment?
- How does your organization impose rules and guidelines to e-rickshaw enterprises?
- How are these rules and guidelines checked and enforced?
- Is it important to know well-connected people to deliver the work documents (information, permits, etc.) that the university/ municipality needs?

Battery shop

Technical

- What are biggest trends nowadays regarding the charging of e-rickshaws? (most used batteries, new laws, subsidies which are important)
- What problems see you the most regarding e-rickshaw batteries?
- Which batteries do you use the most and why? What are the technical properties of these? (Energy density, capacity, efficiency, voltage, discharge rate, costs per kWh)
- Which battery manufactures are you working the most with and why?
- What technical requirements must a battery (manufacturer) meet to include it in your product range?
- What are the drivers and barriers for you and rickshaw drivers to switch to a new battery technology?

Economical

- What is the average cost of an e-rickshaw battery? (Li-ion and lead-acid)
- What is the average lifespan of the battery you are using?
- Are there subsidies that make it attractive for e-rickshaw operators and enterprises to perform their services?
- Is there awareness for these subsidies and how are these communicated?
- Which subsidies play at this moment a dominant role in the e-rickshaw domain?
- Which e-rickshaws with which battery are you selling the most and why?

Social

- What does the structure of your company look like, in terms of managers, employees and business units?

- Are there certain groupings visible in your company, in terms of ethnical background?
- How do your employees solve problems themselves?
- Are your employees trained? Which trainings have they followed?
- How do you ensure that employees handle items neatly? Or does that happen automatically?
- Who makes sure employees follow the planning?
- Do you have a lot of competition?
- Do you sometime collaborate with other actors in the sector?
- Could you give some examples how the Indian government is influencing your
- business practices? Does this have a positive effect or a negative effect?
- How are these rules and guidelines checked and enforced?