Challenges and Opportunities with Continuous Electrode Slurry Mixing in Lithium-Ion Battery Manufacturing

Authors

Alice Gunnarsson	alicegun@chalmers.se
Emil Gunnarsson	emilgun@chalmers.se
Karolina Hedberg	hedbergk@chalmers.se
Nils Svenningsson	nilssv@chalmers.se
Robel Mohammed	robelm@chalmers.se
Wille Runesson	willer@chalmers.se

Supervisor

Jinhua Sun jinhua@chalmers.se

Examiner

Uta Klement uta.klement@chalmers.se

CHALMERS

Department of Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY

Saturday 14th June, 2025

Abstract

The growing demand for lithium-ion batteries has intensified the need for efficient and sustainable manufacturing methods. This literature review investigates the feasibility and potential advantages of continuous slurry mixing compared to the traditional batch mixer for production of lithium-ion batteries. Key performance parameters such as slurry quality, operational efficiency, and production cost are evaluated to compare the two mixing systems. By drawing from scientific literature as well as insights from researchers and industry experts, this study finds that continuous mixing offers clear advantages over batch mixing, particularly in terms of slurry quality and operational efficiency. Furthermore, the study explores why the batch mixer (planetary mixer) remains the industry standard and goes on to assess if the continuous mixer is better suited for potential changes to slurry composition. The findings suggest that continuous mixing is indeed better equipped to handle variations in slurry composition. However, its limited adoption at industrial scale is primarily due to lack of large-scale studies replicating laboratory and pilot-scale experiments, resulting in insufficient data on the industry-scale performance of the twin-screw extruder.

List of acronyms

Below is a list of acronyms used throughout this thesis, listed in alphabetical order:

AM	Active Material
CAPEX	Capital Expenditures
CNF	Carbon Nanofibres
CMC	Carboxymethyl Cellulose
DRC	Democratic Republic of Congo
EV	Electrical Vehicle
LFP	Lithium Iron Phosphate
LIB	Lithium Ion Battery
NBR	Nitrile Rubber
NG	Natural Graphite
NMC	Lithium Nickel Manganese Cobalt Oxide
NMP	1-methyl-2-pyrrolidone
OPEX	Operational Expenditures
PVDF	Polyvinylidene Fluoride
SEI	Solid-Electrolyte Interface
SG	Synthetic Graphite
SBR	Styrene Butadiene Rubber

Contents

1 Introduction

The demand for lithium-ion batteries (LIBs) has been growing at an exponential rate in recent years, primarily due to their central role in modern energy storage solutions [1]. LIBs play a vital role in transitioning to renewable energy by powering various applications such as electric vehicles (EVs), portable electronics, and grid-scale energy storage systems. The widespread adoption of LIBs is driven by different advantages offered compared to other energy storage technologies, including high energy density, long cycle life, and low self-discharge rate [2].

There are different factors that fuel the growth of the LIB demand. A major factor is the shift of the transportation industry towards electrified vehicles and a global push for sustainable energy [3]. This transition has been supported through large investments from industries and governments which have aimed to reduce carbon emissions. In particular, the automotive industry is undergoing a significant transformation where it is moving away from internal combustion engines to electric powertrains, a trend which is expected to accelerate in the coming decades [4].

As demand for LIBs continues to grow, the need for sustainable, efficient, and scalable battery manufacturing becomes an urgent matter. Production must not only scale up to meet global expectations but it has to be in a way that is both economically viable and environmentally sustainable. These demands puts pressure on battery manufacturers to innovate and improve current production processes to ensure that production meet future needs without compromising environmental and economical sustainability.

1.1 Background

More efficient and scalable battery production is becoming essential as the demand for LIBs continues to increase. When a lithium-ion battery is manufactured, the traditional way presents different challenges such as production downtime, material inefficiency, and variability in product quality, which can lead to waste of material. The slurry mixing process, which is the first step in the production line, is a bottleneck in the production process. This step involves blending various components to create a homogeneous mixture. However, in many cases, this process can be inefficient. The slurry mixing process is an important step as it serves as the foundation for the manufacturing of a battery and has a substantial impact on the overall quality of the product and the production efficiency.

To address the previously mentioned challenges, manufacturers have begun to explore alternative manufacturing processes. One of those alternatives is transition towards a continuous production line. The battery industry has yet to implement continuous production on a larger scale, although many other industries have to improve efficiency and scalability. Continuous mixing has already been demonstrated on a laboratory scale and has proven to be a more efficient method [5]. This allows for a streamlined and automated process in which raw materials move through each production stage without interruption [6]. This transition can result in a reduction in production downtime, material waste, and costs, as well as an improvement in product consistency. It is crucial that improvements are made in the battery industry to ensure a sustainable and stable supply of LIBs, especially since there is a growing pressure on manufacturers to improve battery performance and reduce their environmental footprint.

1.2 Purpose

The main focus of this project is to determine whether the switch from batch to continuous processing is feasible for the production of LIBs on an industrial scale. Specifically, the study will focus on the slurry mixing process, which is the first and most consequential step of battery manufacturing. The study will further explore the potential efficiency outcomes of such a transition, as well as identifying key technical, economic, and operational challenges associated with large-scale industrial implementation.

1.3 Boundaries

This study centres on a possible transition from batch to continuous processing for the production of LIBs, focusing solely on the slurry mixing stage in battery manufacturing for EV applications. Therefore, it will primarily look at electrode components that are predominant within the EV industry, which are listed in the table 1. Although other components than those mentioned below will be considered when discussing dry and solvent-reduced electrodes, most of the results will be for slurries made up of the components below.

Table 1: Commonly used cathode and anode components within EV industry.

Components	Cathode	Anode
Active material	Nickel Manganese Cobolt (NMC)	Graphite
Binder	Polyvinylidene fluoride (PVDF)	Carboxymethyl cellulose (CMC)
Conductive additive	Carbon Black	Carbon black
Solvent	1-methyl-2-pyrrolidone (NMP)	Water

Furthermore, this study will not consider the order in which the anode and cathode components are added to the slurry, as this will not help to answer the core research questions in comparing the two mixing methods.

1.4 Research questions

- What are the challenges and opportunities with continuous vs batch mixing in LIB manufacturing?
- Can a continuous slurry mixing process support changes in the LIB-composition?
- Why is continuous slurry mixing not an industrial standard for LIB manufacturing?

2 Theory

This chapter presents the topics: components of LIBs, different mixing systems, and the manufacturing process of LIBs. Lastly, the slurry properties will be thoroughly examined. This lays the foundation for the comparison of continuous and batch electrode-slurry mixing in LIB manufacturing.

2.1 Components of lithium-ion batteries

A LIB is a collection of cells, each cell containing an electrolyte, a separator, two electrodes, and two current collectors located at each end of the electrodes [7] as seen in Figure 1. The two electrodes in the battery are of different charges, the positively charged electrode is called the cathode and the negatively charged electrode is called the anode [8]. One of the most important function of the LIB are the lithium-ions that flow through the battery, making the battery either discharge or recharge depending on the direction the ions flow.

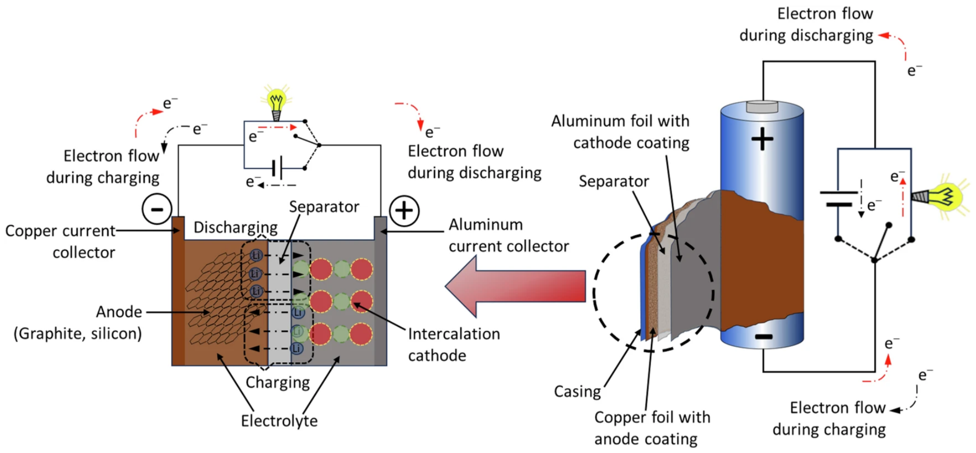

Figure 1: A lithium-ion cell on the left and a representation of how a LIB is built up on the right. Used according with permission from publisher [9].

2.1.1 How the lithium-ion battery works

A battery cell stores energy, which is the charge carriers that are stored in the electrode materials. This is called the potential energy that the material inherit, which is converted into electric energy. The conversion is possible due to a redox reaction that occurs between the cathode and the anode [7], which will be explained in the following paragraph. As mentioned above, depending on which way the lithium-ions (Li^+) flow, the battery will either charge or discharge, see Figure 1. When the ions flow from the anode to the cathode, the battery will discharge implying that the battery is being used. If the flow is the other way around the battery will recharge to later be used again [7]. This is a key advantage of the LIB since not all batteries are able to recharge and can only be used once.

Redox reaction is the combination of an oxidation reaction and a reduction reaction. These reactions occur in the electrodes, which are located at each end of the cell. During the discharge of the battery, an oxidation reaction takes place in the anode where the lithium atoms ionize and lose an electron. The ions then flow to the cathode through a conductive medium, which is the electrolyte and is usually lithium salt dissolved in a solvent. When the ions reach the cathode they recombine with an electron and electrically neutralise. To avoid a short circuit in the battery, the anode and cathode are separated by a membrane thin enough making it possible only for the lithium ions to penetrate [7]. This component is called the separator. When the battery is charging the opposite occurs, the lithium-ions flow from the cathode to the anode and a reduction reaction occurs in the cathode.

2.1.2 Cathode

There are many types of cathodes used in LIBs, depending on the desired properties of the cell. According to [10], the cathode is the heaviest component of the cell and it can be up to 40% the cell's total weight. It is also the component with the most impact on the cell's final performance.

The article [11] states that the cathode is mainly made up of three components, active materials (AM), conductive additives and binders, these are mixed together and seated on a current collector. It is also mentioned that the function of the AM is to be the primary source of energy storage in the LIB. Conductive additives are used to improve the electrical conductivity of the cathode, and biders are used to keep the AM and conductive additives together.

One of the most used AM is Lithium Cobalt Oxide, for short LCO, which has high specific energy and low specific power [12] [11] [13]. This means they can perform under a long period of time in low-load applications, making them suitable for laptops and mobile phones. Another commonly used AM is Lithium Manganese Oxide, also known as LMO, which has high specific power and is able to recharge faster, thus making it suitable for power tools and electric vehicles. The last example of a common AM is Lithium Nickel Manganese Cobalt Oxide (NMC) which has a high specific energy, high energy density and a high thermal stability. This makes NMC one of the most commonly used batteries in EVs.

Nickel has a high energy density, allowing the battery to store more energy [12]. This is desirable in an EV to get longer reach out of each charge and to increase the battery lifespan. All of that is achievable at a relatively low cost. Early NMC batteries used approximately 33% nickel compared to today's batteries containing around 80-90% nickel.

Although manganese has relatively low specific energy, it provides a high-rate capability to the battery, allowing to maintain low temperatures even during high current discharge [12]. This increases the safety and stability of the cell. By lowering the exothermic reaction during charging manganese reduces the risk of thermal runaway, increasing the safety further. Manganese has the ability to reduce deterioration of layered structures inside the cell during charges, thus maintaining the capacity and increasing the lifespan of the battery.

Cobalt helps to provide thermal runaway due to its ability to remain the structural integrity of the cathode during high temperatures [12]. It also helps improving the performance during low temperatures. Due to its ability to increase the discharge capacity, cobalt increases the energy density of the cell. Finally, cobalt improves the rate performance, allowing for faster charging.

2.1.3 Anode

The anode, together with the cathode, forms the two electrodes in a battery cell, and they have much in common. Like the cathode, the anode is composed of an active material, conductive additives, and a binder, which are then coated onto a current collector, typically made of copper foil [14]. These components serve similar functions as in the cathode: the active material acts as the primary medium for energy storage, the conductive additives improve the electrode's electrical conductivity, and the binder holds the particles together and ensures strong adhesion to the current collector. Just like cathodes, anodes are available in different variants, utilizing various active materials depending on the specific application. Anodes are generally less expensive than cathodes. According to [15] the anode accounts for around 10–15% of the total cell cost, compared to approximately 40% for the cathode.

Graphite is the most commonly used AM in EVs today, dominating the market with over a 90% market share [16]. This is due to its relatively low cost, good cycling stability, reliable capacity, and ability to deliver high cell voltage when paired with appropriate cathode materials [16]. Although graphite remains by far the most commonly used anode material in LIBs today, alternative materials such as lithium titanate and silicon have also begun to gain attention. Compared to graphite, silicon offers a much higher specific capacity, approximately 4,200 mAh/g versus 372 mAh/g for graphite, making it a highly promising candidate for future anodes [17] [18]. However, silicon undergoes significant volume expansion during the lithiation and delithiation processes, which introduces mechanical stress in the anode. This stress can lead to cracking and pulverization of the material, ultimately degrading the electrode's electrochemical performance [19] [20].

Lithium titanate, on the other hand, experiences negligible volume change during cycling, resulting in much less mechanical strain and contributing to a significantly longer anode lifespan [21]. Additionally, lithium titanate has a higher lithium intercalation potential ($\approx$ 1.55V Li/Li$^+$) compared to graphite ($\approx$ 0.1–0.2 V) [22]. Higher lithium intercalation potential makes the anode less susceptible to lithium plating, when metallic lithium deposits on the surface of the anode potentially causing short circuits and thermal runaway, thus enhancing battery safety [22]. However, this higher potential also reduces the overall cell voltage and energy density. Lithium titanate's specific capacity is also lower, around 175 mAh/g, which along with its lower energy density, still makes graphite the most suitable choice for most current applications [21].

2.2 Industrial mixing systems

Industrial mixing systems create uniform mixtures or products by combining, blending, or homogenizing different materials. These mixers are used to achieve consistent and efficient mixing of ingredients or components. Industrial mixers are used in various settings, from small-scale laboratory work to large-scale manufacturing processes, and can be divided into two types, batch and continuous mixing processes.

2.2.1 Batch mixing

In batch manufacturing, the products are made in discrete volumes, called batches [23]. This makes the process run in a cycle with a finite operating time, where the process needs to be reset to its pre-process condition before continuing with a new cycle. Resetting the process creates downtime when the equipment needs to, for example, be cleaned, reheated, or cooled down, and this is the main disadvantage in batch manufacturing, as it limits the production speed [24]. Batch production enables the ability to change the ingoing components to create new products with each batch. This makes batch mixers preferred when changes in the composition between batches are needed. Hence, batch mixers are often used in laboratory settings when multiple compositions are tested. However, since each batch is filled separately, variations between batches can occur. A batch that does not reach the desired quality is often wasted, leading to increased materials use.

Batch mixers are most commonly used in facilities that do not need a high production speed, but require a product of high quality or to create different products in the same equipment [24]. Since products are made in batches, the resulting production speed becomes uneven, which can affect the rest of the production chain. However, batch production allows one to easily verify the quality of each batch before sending it to the next step in the production chain [25]. This makes batch mixers a common equipment when a high-quality product is needed. It should be noted that other high-quality product manufacturers, such as the pharmaceutical industry, are replacing batch mixers with more continuous types of mixers [26].

2.2.2 Continuous mixing

The concept of continuous mixing is thoroughly discussed in the article [27], which presents several important characteristics and considerations regarding this technology. The article describes that continuous mixing is a process in which the ingredients are fed into the mixer in a continuous stream without interruptions. The final mixed product is then discharged at the other end of the mixing vessel. This setup eliminates the need for separate steps for filling, mixing, and emptying. As a result, it streamlines the production process and increases efficiency, allowing for higher production capacity. Due to this, the continuous system is suitable for large-scale manufacturing, which requires a high production rate and minimal downtime. To oversee the continuous mixing process and to ensure the quality of the final mixed product, the process requires advanced monitoring and regulation systems. This includes measurement equipment to ensure that the correct proportions are added to the mixer in real time. As a result of the advanced monitoring and regulation system, the continuous mixing system is usually a larger initial investment than a batch mixing system. Additionally, altering the ingredient ratios causes a delay before stabilisation, which can make defect traceability in production difficult. However, within industries where consistency in batch quality is critical, the implementation of continuous systems can provide high levels of control over ingredient measurement and processing. While the composition of ingredients can be adjusted within a continuous mixing system, changing to a different formulation requires stopping the process and thorough cleaning. This makes continuous mixing most efficient for large-scale production of a single product type where quality consistency is essential.

Staggert presents in the article [28] that industries that commonly utilise continuous mixing include pharmaceuticals, chemicals, polymer production, and pulp manufacturing. The article continues to explain the implementation of the continuous process in these industries. High-volume tablet production and continuous granulation are processes in the pharmaceutical industry suitable to be handled using continuous mixers. In the chemical industry, continuous-mixing utilisation is implemented for effective polymer production, fertiliser manufacturing, and detergent production. Continuous mixers are utilised for pulp preparation and coating processes in pulp production.

2.3 Battery manufacturing

As mentioned in the introduction, LIBs has numerous of applications and thus come in various shapes and forms. In the article [14] it is mentioned that despite the diversity in LIB types, the basic manufacturing steps remain mostly the same across different designs. These steps are generally consistent regardless of the battery's shape, the materials used in the electrodes, or the scale of production, whether large or small.

The article [14] also states that the most common used production technique of LIB today can be divided into four major steps, extraction of raw materials, preparation of the electrodes, cell manufacturing, and finally chemical activation of the cell. Each of these main steps are further divided into several sub-steps.

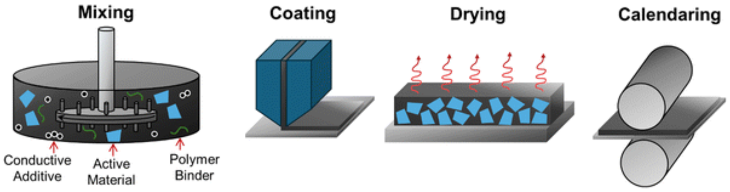

Figure 2: The first manufacturing steps of LIB. Used according with permission from publisher [29].

The tables 2 and 3 below presents some of the sub-steps along with their corresponding energy consumption and estimated costs. Further details will be provided in the sections that follow. The data in the tables below are made using data from the article "Current and future lithium-ion battery manufacturing" [14].

Table 2: Energy use in LIB manufacturing sub-steps. With data from [14]

Process Step	**Energy Use (kWh/cell)**	**Percentage (%)**
Slurry mixing	0.11	0.83
Coating	0.18	1.36
Drying/Solvent recovery	6.22	46.84
Calendering	0.38	2.86
Slittig	0.71	5.53
Stacking	0.77	5.90
Welding	0.25	1.88
Enlosing	0.69	5.20
Formation/Aging	0.07	0.53
Dry room	3.9	29.37

Table 3: Cost LIB manufacturing sub-steps. With data from [14]

Process Step	**Cost per year percentage (%)**
Slurry mixing	7.91
Coating/Drying	14.96
Solvent recovery	4.60
Calendering	5.19
Slittig	3.09
Vacuum drying	3.20
Stacking	8.65
Welding	7.34
Enlosing	12.45
Formation/Aging	32.61

2.3.1 Mining

Before the battery manufacturing can start, raw materials must be obtained. Depending on the composition of the materials that make up the cathode in LIB, the metals that need to be obtained vary. For NMC, the metals are lithium, nickel, manganese, and cobalt, and they are acquired through mining.

Lithium is mainly sourced from two deposits: brine and hard rock. From hard rock mining, lithium minerals can be extracted from spodumene ore, which is then processed to obtain lithium hydroxide or carbonate [30]. The source further states that to extract lithium brine, lithium-rich groundwater is pumped into evaporation ponds where the lithium is later concentrated before being chemically processed. Between the two methods of extracting lithium, brine extraction requires less energy but instead requires significant water resources.

Primarily, nickel is mined from laterite and sulfide ores, and due to impurities from laterite mining, it requires extensive processing [31]. Cobalt is one of the by-products of mining nickel and copper, and it has drawn attention because of ethical concerns regarding the mining [32]. Mining is predominantly carried out in the Democratic Republic of Congo (DRC), where child labor and poor working conditions are common [33]. Lastly, the most common method to extract manganese is through open-pit mining from sedimentary and lateritic deposits [34].

2.3.2 Slurry mixing

The first step in preparation of the electrode is to mix AM, binder, conductive additive, and solvent into a homogenous slurry [14]. According to the same source, the conventional slurry mixing step accounts for approximately 7.91% (see table 3) of the total annual manufacturing cost, making it one of the most expensive steps in the process. This high cost is primarily due to its labour-intensive nature. It is important that the slurry is thoroughly mixed, since the distribution of AM, binder, and conductive additive in the slurry has a major impact on the final performance of the LIB [35]. Although there are various methods of slurry mixing today, the most commonly used technique is to use a planetary mixer [36] [37].

Planetary mixers are the conventional type of mixer when it comes to slurry mixing [36]. It is a batch mixing equipment, where the unmixed substances are first loaded into the mixer and then later, in the end, unloaded as a mixture [24]. To visualise a planetary mixer, it can be compared to a dough mixer, made up of a large container with some type of mixer inside that mechanically mixes the components. In the mixer, conditions such as temperature and mixing speed can be controlled to create a good mixing environment. Compared to other batch mixing equipment, the planetary mixer is fairly good at handling a bit more viscous slurries, making it a versatile equipment. However, it still requires quite a lot of solvent in order to form a homogeneous mixture.

2.3.3 Coating, drying, and calendering

Next sub-step in the electrode preparation is coating. Using a slot die the slurry is coated onto the current collector. Aluminium foil and copper foil is used as current collector for the cathode and anode respectively [14].

Following the coating process, the electrodes are dried to evaporate the solvent. According to [14], the drying sub-step has the highest energy consumption, 46.84% of the total energy consumption (see table 2). Coating and drying are also among the most expensive steps in the manufacturing process, accounting for 14.96% of the total annual manufacturing cost (see table 3). While water can be safely realised into the environment. 1-methyl-2-pyrrolidone (NMP) is toxic, thus a process to recover the NMP is necessary [14]. In [38] it is mentioned how the drying step significantly influences the microstructure of the electrode. High drying speeds tend to cause the binder to migrate out of the slurry, leading to a heterogeneous electrode structure. This negatively impacts the electrochemical performance of the cell. According to [39] can poor binder distribution also reduces the slurry's adhesion to the current collector, ultimately shortening the electrode's lifespan. In [40] it is therefore mentioned how a trade-off must be made between manufacturing speed and electrode performance. The most common approach to managing this trade-off is through conductive drying, where the drying temperature is gradually reduced as the amount of remaining solvent decreases.

After the slurry has been coated onto the current collector and the solvent has been recovered, a calendering step follows. Calendering enhances battery performance by increasing the energy density [41]. By reducing the porosity of the electrodes, calendering has also been shown to improve both the rate performance and cycle life of the battery [42] [43]. The same sources also mentions that calendering improves the mechanical performance of the electrode, thereby increasing its lifespan. For example, it enhances the adhesion between the slurry and the current collector. Additionally, calendering can reduce lattice strain and phase transitions in the electrode, which are common causes of cracking and structural failure of the electrode.

2.3.4 Cell assembly and activation

The second major step is to assembly the cell. Electrodes and separators are winded or stacked together, in this way forming the inside structure of the cell. An aluminium tab is welded on to the cathode and a copper tab is welded on to the anode [14]. There are a few different methods used to weld the tabs on to the electrodes, but the most commonly used are ultrasonic welding and resistance welding [14]. The electrodes are then put inside the case and, which then is filled with electrolyte before sealing the case.

The final steps are the electrochemical activation steps. These steps are performed by first charging the battery to a low voltage, this to prevent corrosion in the copper current, then letting the battery rest for electrolyte wetting, this process is called formation. By charging and discharging the battery, the stability of the solid-electrolyte interface (SEI) is increased between the electrolyte and the electrode [14] [44]. In [45] it is stated that SEI blocks the electrons but allows for transportation of lithium-ions, thus preventing electrolyte decomposition. The cells are then stored for ageing for complete electrolyte wetting and SEI stabilisation [14]. The cell then goes through a degassing step before finally being sealed.

2.4 Slurry

As explained in the previous chapter, the preparation of the electrode slurry is the first step in the production of LIBs and as such plays an important role in the intrinsic properties of the final product as well as the manufacturing efficiency of subsequent steps. Electrode slurry is a multiphase suspension consisting of active material, conductive additives, binder and solvent. All of which are dispersed within the electrode slurry and together will form the cathode and anode layers in the LIBs.

2.4.1 Active materials

This project focuses on the most common active materials used for the cathode and anode in the EV industry. The active material is the largest component in the slurry in terms of particle size and is detrimental for both the electrochemical and rheological performance of the electrode slurry [29]. Which in turn has significant implications to the slurry mixing process. For instance, the slurry's yield stress which is the minimum stress required to start flow is highly dependent on the particle size of the active material [29].

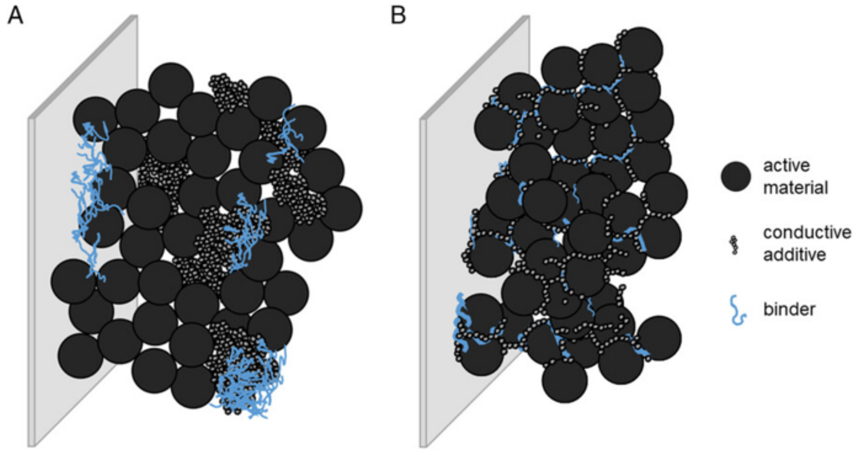

Figure 3: An illustration comparing two cathode microstructures: (A) shows large-scale agglomeration, while (B) presents a uniform cathode microstructure with no agglomeration and a well-dispersed binder. Used according with permission from publisher [37].

Favoured for its high energy density, NMC is currently the most widely used material to produce the cathode within the EV industry. Although NMC has great electrochemical properties, it does present challenges to the electrode mixing process, the most prominent of which is its tendency to agglomerate. Jianlin Li et al. explains in [46] that this is due to van der Waals forces between NMC and conductive additive particles, which makes the particles "stick" together and form clumps in the slurry as illustrated in figure 3 microstructure (A). This limits electron pathways which harm electrochemical performance as well as increasing viscosity. Carl D Reynolds et al. further elaborate that for increasingly small active materials the intermolecular forces are magnified due to increasingly larger surface area, which further increases the viscosity of the slurry. This means that decreasing the size of the active material directly results in increasing the amount of shear needed to overcome the van der Waals forces [46]. Another important challenge to consider is sedimentation, due to its high density NMC is prone to rapid sedimentation. Sedimentation creates non-uniform coating which can result in inconsistencies in the final electrode. Sedimentation is deterred by sufficiently high viscosity at rest [47].

High electrical conductivity and structural integrity has made graphite the most prominent active material for the anode. As with the cathode slurry, the size and shape of the graphite particles significantly influence the rheological properties of the anode slurry. As highlighted by a study from Yeeun Kim et al., graphite can be categorized in two types; differentiated by the way in which the graphite is manufactured. Natural graphite (NG) is mined and thereafter refined and synthetic graphite (SG) is derived from petroleum. The most important difference between NG and SG in regards to this study is the resulting size and morphology of respective graphite type. NG particles are spherical and exhibit irregular particle size distribution, which contribute to higher viscosity and yield stress. While SG particles are more homogeneous in size and exhibit a disc-like shape, which makes them easier to mix and homogeneously disperse within the slurry [48]. Graphite's hydrophobic nature is also known to pose challenges to water-based slurries, the agglomeration of graphite particles being the biggest concern [49].

2.4.2 Binder and solvents

The most used binder for NMC cathodes is polyvinylidene fluoride (PVDF) and the industry standard solvent for PVDF is NMP. The polymeric binder dissolved in the organic solvent serves multiple crucial functions within the electrode slurry that collectively ensures the electrochemical and structural integrity of the electrode. A previously mentioned study from the journal of chemical reviews states that one of the key functions of the binder is particle binding; the binder coheres the active material and conductive additives together in the slurry. The binder further adheres the electrode slurry onto the current collector (i.e. aluminium foil) and provides structural flexibility. This flexibility helps to prevents deterioration in subsequent manufactural steps like coating, drying, etc. [46]. For the binder to effectively perform its critical functions, it is vital to carefully consider two major factors. The first is binder content: too much binder will increase cell impedance due to PVDF being electrochemically inert. Conversely, insufficient binder content will lead to poor adhesion and cohesion capabilities, potentially leading to crack formation on the electrode and even separation from current collector [50]. The second factor is the uniform dispersion of the binder within the slurry, which is essential for maintaining the electrode's internal structural integrity and ensuring strong adhesion to the current collector. An example of an electrode with well dispersed binder can be seen in figure 3 microstructure (B).

Carboxymethyl cellulose (CMC) is the most common binder for the anode slurry and due to its water solubility, the most commonly used solvent is water. It is worth noting that in some cases, styrene butadiene rubber (SBR) is added to the binder as a reinforcement agent. As described by Masahiko Ishii et al., one of the ways that CMC improves the rheology of the slurry is by directly preventing agglomeration of graphite particles by adsorbing onto graphite surfaces via hydrogen bonding. The negatively charged carboxyl group in CMC creates a repulsive force in between particles that prevents aggregation [51]. Furthermore, CMC is also able to create a complex polymer network in water thanks to its hydrophilic carboxyl group that increases viscosity at rest by restricting fluid motion. This is vital for preventing sedimentation of graphite particles at rest [52]. CMC is also known to exhibit shear thinning properties where the polymer chains align in the direction of flow, which allows the slurry to flow easily under high-rate sheer mixing and coating, while recovering high viscosity once mechanical stress is removed. This allows for homogeneous dispersion of active materials and conductive additives as well as a maintained structural integrity once the slurry is coated on the current collector [53].

2.4.3 Conductive additives

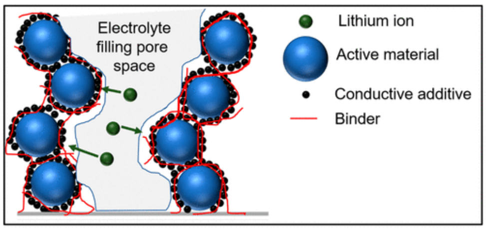

Figure 4: Illustration of how conductive additive particles bridge the gap in-between active material particles. Used according with permission from publisher [46].

Carbon black is the prevalent conductive additive for LIB-NMC, due to its excellent electronic conductivity properties. As explained in a 2024 study from the Journal of Power Sources, carbon blacks characteristic properties stem from its large surface area and its ability to form a percolative network within the slurry, which facilitates efficient electron transport [54]. Its nanoscale size makes it easy to bridge the gap in between NMC particles as demonstrated in figure 4, which enhances the slurry's conductive capabilities [46]. However, Reynolds et al. notes in a 2023 study that the small size and large surface area of carbon black also give it a tendency to agglomerate, necessitating intensive mixing to break apart [55]. Furthermore, it is also vital to consider the amount of conductive added, as too much carbon black yields diminishing returns in terms of conductivity while unnecessarily increasing viscosity due to large scale agglomeration. On the other hand, if the amount of carbon black is not enough to form the percolative network then regions of the electrode may become electronically insulated increasing resistance within the electrode. This leads to the conclusion that the amount of carbon black added to the slurry should be just enough to establish a percolative network [54].

As for the cathode slurry, carbon black is the predominant conductive additive for the anode slurry as well [55]. Although the anode slurry is water-based, the conductive additive performs largely similar function in both slurries. As previously explained, carbon black bridges gaps between active material particles, which creates a network that facilitates efficient electron transport. What is not previously mentioned is that this percolating network also restricts particle movement within the slurry, increasing the viscosity at rest or under low shear, but during mixing or coating this network breaks down, dramatically reducing viscosity. This phenomenon is called shear-thinning and it allows the slurry to be easily mixed under shear, but also rapidly regain viscosity after mixing to help prevent sedimentation.

2.4.4 Slurry composition

The total solid content of the cathode slurry during mixing should range between 63.9-66.3wt%, with the remainder consisting of solvent. This distribution of solid content within the multiphase suspension is shown to promote uniform distribution of active material and conductive additive [56]. After solvent removal, the slurry composition strongly favours a high fraction of active material with a small amount of binder and conductive additive. A common formulation being 90-95wt% NMC, 2-5wt% PVDF and 2-5wt% carbon black. This composition optimises energy density by minimising inactive materials, whilst maintaining sufficient binder content for cohesion/adhesion and enough conductive additive to establish percolative network [57]. This balance represents the optimal compromise between electrochemical and rheology performance of the cathode electrode [46].

As stated in the following studies [53] [46] [58], an industrial grade anode slurry has an optimised composition of roughly 50wt% solid content, with the remainder being water. After solvent removal, the solid composition is typically 90-95wt% graphite, 3-5wt% CMC and 1-5wt% carbon black. Similar to the cathode slurry, the aim is to maximise energy density without compromising structural integrity or conductivity.

3 Methodology

To answer the research questions, a systematic literature review and complementary interviews with specialists in the industry were conducted. This contributed to a comprehensive understanding of the problem, which was required to produce a nuanced result. The following chapter describes the literature review and the interviews in greater detail.

3.1 Systematic literature review

A systematic literature review was conducted. The aim of the review was to synthesise and analyse both qualitative and quantitative findings from the available literature regarding the possibilities and potential benefits of continuous slurry mixing in LIB manufacturing. Focus is placed on identifying common themes and patterns in the selected articles in order to address the research questions.

3.1.1 Literature search

Relevant sources were searched for in the databases Scopus, ArXiv, IEEE Xplore, and Google Scholar. The search strings were constructed with the key words such as ”lithium-ion battery”, ”slurry mixing”, and ”continuous manufacturing” and Boolean operators. An example of a search string used in Google Scholar:

> (”lithium battery” AND ”continuous slurry mixing”)

To complement and enhance the search, Scopus AI was used. This tool allows users to pose specific research questions, providing responses based on relevant articles from the database, which are also listed for further reading. The search results were manually evaluated to ensure that the inclusion criteria were met. This approach was implemented to ensure that no important sources relevant to the topic were overlooked. Example of question asked in Scopus AI:

> ”What are the benefits with continuous slurry mixing for lithium-ion battery manufacturing?”

In addition to Scopus AI, ChatGPT (OpenAI, 2024) was also used to suggest additional potential articles. All suggestions from both Scopus AI and ChatGPT were manually reviewed to ensure they met the inclusion criteria and were relevant to the aim of the study.

3.1.2 Study selection

The included studies consisted of both qualitative and quantitative findings. During the selection process, duplicate records were identified and removed. The remaining articles were screened based on the predefined inclusion and exclusion criteria. Each article was first assessed based on its title and abstract, and then evaluated in full text to determine its relevance to the research question. Source evaluation followed the CRAAP model [59], ensuring that all included studies were current, accurate, objective, relevant, and published by credible outlets.

Studies were excluded if the full text was not accessible or if they did not meet the predefined inclusion criteria. Inclusion required that studies fulfilled the following criteria:

- Published between 2010 och 2025
- Written in English
- Discussing the slurry mixing stage of LIB manufacturing

No formal protocol was maintained for the articles excluded during the selection process, and detailed justifications for specific exclusions were not documented. This represents a limitation in the transparency of the study. The issue of documenting the selection process and exclusions in a more systematic manner will be further addressed in the discussion section.

3.1.3 Qualitative synthesis and thematic analysis

A qualitative synthesis and thematic analysis were conducted to identify recurring themes and patterns within the included studies. Data from each article were extracted and organised to identify key themes and patterns. Through this synthesis, it was possible to draw overarching conclusions about continuous slurry mixing for LIB manufacturing and identify common trends in the research.

The synthesis process was conducted through the following steps:

1. **Data Extraction:** Relevant data from each article (e.g., results, conclusions, methods) were extracted and organised.
2. **Thematic Analysis:** Through thematic analysis, the results were categorized to identify common and divergent themes.
3. **Synthesis:** The identified themes were combined to create an overarching understanding of the research area and the main findings from the articles.

3.1.4 Selection chart

Since a complete selection protocol was not maintained during the literature search, only the number of included articles is reported. An approximate total number of articles was estimated using the search term "continuous production lithium battery" in Web of Science, which gave 361 results [60]. A flowchart of the selection has been created to provide an overview of the process.

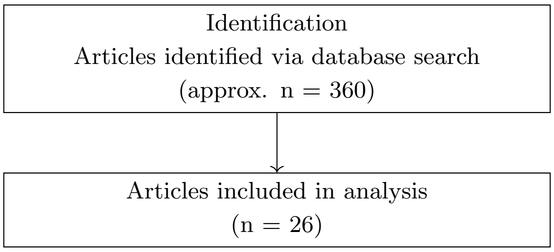

Figure 5: Flowchart of the selection process.

3.2 Interview with sector specialists

To complement the findings of the systematic review and provide deeper insights into a potential transition of standard mixing equipment in LIB manufacturing, interviews with sector specialists were conducted. The interviews aimed to capture practical experiences, opinions, and perceived barriers from professionals in the field, with the intention of including diverse perspectives across the field.

Participants were selected through purposeful sampling, focusing on individuals with relevant expertise or roles in LIB production and research. Initial contacts were identified by the project group, and additional candidates were found using snowball sampling, based on recommendations from earlier interviewees. The interviews were semi-structured, guided by predefined questions tailored to each participant's background and the study's thematic focus. Details regarding the selection of participants, the interview process, and methods for data collection and analysis are presented in the following sections.

3.2.1 Selection of interview participants

Participants were selected through purposeful sampling, based on their roles in the battery manufacturing sector. Both researchers, equipment suppliers, and manufacturers were represented to create a well-rounded understanding of the topic. The selection process combined direct outreach and snowball sampling, where new candidates were identified through recommendations from previous interviewees.

The first participant selected was a former University Relations Manager at Northvolt, in Stockholm, Sweden, chosen to provide insights from the manufacturer's perspective [61]. Their experience in the battery manufacturing industry made them a valuable source of insight into the decision-making process during the design phase of production lines, particularly regarding the evaluation of mixing equipment. This participant was identified and contacted through email and LinkedIn, and after initial communication, an interview was arranged.

The second participant is Carola Rindi, a Research Associate at Fraunhofer Research Institution for Battery Cell Production (FFB), in Münster, Germany, chosen for her expertise in production technologies, particularly in slurry mixing, coating, and drying processes. Their work with pilot-scale systems, including twin-screw extruders, provided significant insights into the technological development and research aspects of LIB manufacturing [62]. This participant was identified through a recommendation during the interview with the first participant. Subsequently, Fraunhofer FFB was reached out to via email, establishing contact and arranging the interview.

The third participant is Dave Collins, UK and Nordics Area Sales Manager for battery mixing at Bühler Group, located in London, UK (Head Quarters located in Switzerland), a leading supplier of continuous mixing technology for battery manufacturing.Bühler has extensive experience in implementing continuous slurry mixing technology worldwide, with over 15 years in the industry. Bühler have delivered more than 80 continuous mixing lines to the LIB industry corresponding to more than 100 GWh in annual production capacity. The majority of these continuous production lines have been delivered to China, which today clearly dominates the LIB market. This participant was selected to provide the supplier's perspective on the practical application of twin-screw extruders [63]. The initial contact was made through Bühler's central email address, which led to connecting with the area sales manager. After further communication, an interview was arranged.

3.2.2 Process of interviews

The interviews was carried out as a semi-structured interview with questions prepared and sent to the candidates beforehand to give them time and the opportunity to answer the questions as good as possible. All interviews was done online in a meeting call. The lengths of the interviews varied, but a timeline of around 30-45 minutes was set depending on the amount of questions sent. A request to record the interview was sent to each candidate in which only Carola Rindi from Fraunhofer FFB accepted, but notes were taken during every interview. Permission to use all interviews in this report was also accepted by all candidates. A chairperson and secretary was decided before every interview in order to make them more effective and organised, a person from the project group was also responsible to make the roughly taken notes usable in the report.

3.2.3 Interview questions

All interview questions that were asked to each candidate can be found in appendix A. The thought process behind the questions was aimed towards the different expertise of the candidate. For the candidate from Fraunhofer FFB, the questions was aimed toward the research aspect in battery manufacturing since they are more research inclined. As for the representative from Bühler, the questions was more aimed towards a suppliers perspective and how the market currently is regarding continuous mixing lines. Lastly the questions asked for the Martin Karlsson was specified from a manufacturers point of view.

3.2.4 Analyse of interviews

As mentioned above, one of the interviewers present had the responsibility to go through the interviews. This could include the notes, eventual recordings and transcriptions. The main object was to collect data that the candidates contributed to and make a qualitative interpretation of the given parameters. They were also assigned to take the interviews (e.g notes) and summarise the responses in order to be able to write a result.

3.3 Approach to AI-tools

It is mentioned earlier in this section that Scopius AI and ChatGPT have been used to find sources that are then evaluated with the CRAAP model [59]. ChatGPT is also used together with Writefull for grammatical correction of the project text directly in the Overleaf LaTeX editor, in which both tools are integrated. Writefull is a language feedback system created for research writing that has been trained on published papers [64]. Only the free version of Writefull was used in this project, limiting the number of language suggestions. Grammatical correction was also done by manually adding text to ChatGPT's chat function. In addition to this, the chat function was used to find suitable synonyms and to sort through the attached sources found and evaluated with the CRAAP model [59]. The use of generated text in the report was avoided to all extent.

4 Results

As previously mentioned, slurry mixing is a critical step in the manufacturing of LIBs. It has a direct influence on the quality of the electrode, the consistency, and the overall performance of the cell. Currently, the slurry mixing process takes place in a batch mixer, most commonly a planetary mixer. In the result, the opportunities and disadvantages of transitioning to a continuous mixing process are presented. The reviewed literature [46] highlights the twin-screw extruder as a viable continuous alternative for LIB manufacturing. This section begins with an introduction of the twin-screw extruder, followed by a comparison with the planetary mixer. The findings then outline the reported potential for adapting twin-screw technology to accommodate future LIB formulations. Finally, insights from interviews with industry representatives are presented, focusing on the standardisation of mixing equipment. The interviewees also highlighted technical differences between the systems, which proved valuable considering the limited number of publicly available literature discovered in the literature review.

4.1 Twin-screw extruder

A twin-screw extrusion is a type of continuous mixing system which is feasible for the slurry production in LIB manufacturing according to the studied literature [46]. It is explained in [28] that the mixing system consists of two screws rotating within a cylindrical barrel. These screws can be parallel or conically designed and either co-rotating or counter-rotating. With co-rotating parallel screws, the optimal compounding performance is obtained for electrode slurry. Electrode-component powders are fed into the screws through an inlet port at the beginning of the tube. Between the screws and the barrel wall the material is sheared as the screws rotate and move the material along. Using solvents, the slurry is dispersed as it works its way down the barrel. At the end of the barrel the compounding material is pushed through a die slot which distributes the slurry onto the current collector in the coating step. The whole process through the tube can be controlled, which includes the screw speed, feed rate, and temperatures of various zones of the mixing vessel [28].

The barrel of the twin-screw extruder is typically divided into alternating conveying and compounding zones (see figure 6), often in two or three stages. Near the inlet port, the screw gap is wider to minimise the risk of blockages when the dry components are introduced. The first conveying zone serves to transport the dry slurry components, and it is common for liquids to be introduced here. Next follows a compounding zone where the screw design changes to introduce shear forces, initiating the mixing of the slurry. This is followed by another conveying zone, where additional powders or liquids can be added to the mixture. The second compounding zone continues the mixing process to ensure homogeneity. Toward the end of the barrel, a final conveying zone allows for venting, where gases or volatile compounds can be removed through vent ports, if necessary. Pressure is then built up before the material is extruded through the die slot. This segmented design enables tailoring to different applications and different compositions [28].

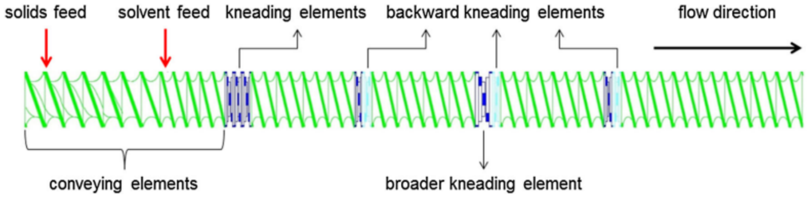

Figure 6: An illustration of Twin screw extruder.Used according with permission from publisher [65].

Continuous slurry mixing is gaining increasing attention as an alternative to batch processing. Several commercial suppliers have already brought twin-screw extruder systems for electrode slurry mixing to market, such as Bühler based in Germany and Longly based in China. Research initiatives on electrode slurry production using twin-screw extruders also exist, including efforts at institutions such as Fraunhofer Research Institution for Battery Cell Production FFB in Münster, Germany. However, the limited number of publicly available academic publications identified during the review suggests that much of the development in this field is being carried out in-house by companies, rather than in publicly funded research.

4.2 Comparison between planetary mixer and twin-screw extruder

The planetary mixer is currently the most commonly used mixer in slurry production according to [66], [14], and [67]. To highlight the differences between planetary mixers and twin-screw extruders, the two technologies will be compared. This will be evaluated in terms of technical performance, sustainable impact, and economic-related advantages and disadvantages.

4.2.1 Production time

Literature by Stuggert [28], Liu Yangtao et al. [14], and Li, Jianlin et al. [46] consistently reports that the mixing time is one of the most distinguishing factors between the planetary mixer and the twin-screw extruder. According to the source [14], the mixing time for the planetary mixer is around 30 minutes - 5 h. The presented mixing time in the source [46] is 3-8 h. It is mentioned in both articles that the large variation of time range depends on the chemistry and batch size. Additionally, the planetary mixer needs to be emptied and cleaned before the next batch, which adds 1-2 more hours according to [66]. In contrast, the twin-screw extruder has the reported residence time in order of minutes presented in [46]. Additionally, it is stated in the same article that the twin-screw extruder does not necessitate cleaning or stopping as long as the slurry components are maintained, which is confirmed by Carola Rindi, the interviewed researcher associate [62].

Due to the long mixing time in the planetary mixer, logistical issues have been reported in the article [46], which causes delays between the mixing and coating stages. The slurry exhibits time-dependent properties that can change when not continuously mixed, potentially leading to variations in the final product when the batch is not coated immediately. This issue is mitigated with twin-screw extruders, as the continuous process enables immediate coating after slurry preparation. According to [46] a steady flow of slurry into coating is also crucial for even drying and inherently the performance of the battery. However, when the slurry mixing stage using a twin-screw extruder is directly connected to the coating and drying stages, any disturbance in one of the unit operations may lead to the shutdown or restart of the entire process, as noted in [46].

4.2.2 Production volume

One of the largest twin-screw extruders for electrode-slurry mixing, available on the market, delivers at max capacity 3000 l/h reported by the company Bühler [63]. Additionally, the article [46] reports that twin-screw extruders can deliver 2400 l/h. Due to technical limitations, a planetary mixer cannot accommodate the same production rate as the largest twin-screw extruders. According to [46], scaling the batch volume to reach closer to 2000 l introduces significant difficulties. One major issue mentioned is the increased power demand required for adequate mixing. Cited in the same article, "The amount of power required to put work into the mixing process becomes cost-prohibitive on a power-per-volume basis," making it difficult to maintain slurry homogeneity and product quality at larger volumes. Therefore, instead of increasing the batch volume, production rate is increased by adding additional mixers, which is also mentioned in [46]. As a consequence, [46] states that with a continuous mixing system operating at an average production rate of 12.000 l/h (corresponding to a 35 GWh/year production capacity) the number of extruders required is approximately one-fifth of the number of parallel planetary mixers in an equivalent batch system.

The same study [46] presents that, in the specific scenario descried above, the continuous mixing system can reduce floor space requirements by approximately 30 %, as a result of the lower number of required twin-screw extruders. This trend is also reflected in industry sources. In a product presentation by Bühler [63], it is stated that one 125 mm twin-screw extruder (3,000 l/h throughput) is equivalent in cell capacity to approximately six planetary mixers (1,500 l each), with a potential 50 % reduced floor space requirements. While not peer-reviewed, this source provides an additional indication of the potential advantages of continuous mixing in large-scale production.

Due to the same fact that fewer twin-screw extruders are required to achieve the same production rate, and that the slurry volume within the system at any given moment is significantly lower compared to batch processes, the total energy consumption is reduced, according to [67] and [28]. However, the exact magnitude of these energy savings was not determined in the studies, and quantifiable data on this topic remains limited in the available literature.

It is mentioned in [46] and [28] that multiple planetary mixers are more labour-intensive compared to twin-screw extruders. This is partly due to the need to empty and clean each batch between cycles, which requires manual handling and is time-consuming according to [46]. As previously mentioned, the article states that achieving the same production rate as a continuous mixing system requires a larger number of batch mixers, which in turn increases the number of units that must be monitored and maintained, further contributing to the overall labour intensity.

4.2.3 Slurry quality

As described in section 2.4.2 Binder and solvents, adhesion is a measure of how well the dried slurry sticks to the current collector, whereas cohesion is a measure of how well the internal components hold together. Both adhesion and cohesion are essential parameters/indicators for the quality of the slurry, and the ultimate performance of the finished product. Therefore, it is relevant to ascertain how these parameters compare between slurries prepared by a continuous mixing process (twin-screw extruder) versus one produced by batch mixing (usually planetary mixer).

Studies indicate that with proper formulation both batch and continuous-mixing produce cathode slurries with sufficient adhesion capabilities. In fact, adhesive failure is generally not considered a prominent point of failure for either mixing method [65]. On the other hand, cohesive failure is shown to be more commonly observed problem for the cathode slurry. A study from the Journal of Electronic Materials reports a cohesive failure for the cathode slurry produced by twin-screw extrusion at 1.3-1.45 MPa and 1.2-1.3 MPa, respectively, for the cathode slurry produced by a batch mixer [65]; no adhesion failure was observed at those levels. When it comes to the anode slurry, the binder is the predominant factor responsible for adhesion and cohesion capabilities, and as such, adhesion and cohesion strengths are directly tied to how well the binder is dispersed within the slurry [68]. Furthermore, a previously mentioned study also showed that both mixing methods disperse the binder equally well within the slurry [65]. Although no direct comparison of adhesion and cohesion strengths could be found for the anode slurry within the literature, it is a reasonable extrapolation that an equally well-mixed binder will result in no difference in adhesion and cohesion strength between the two mixing methods. In summary, the twin-screw extruder maintains the same levels of adhesion and cohesion capabilities within the electrode slurry, if not slightly better than batch [65].

As explained in section 2.4 Slurry, the homogeneous distribution of binder, conductive additive, and active material is the most crucial factor for the overall performance of the finished product. Therefore, the most important point of comparison between these two mixing methods is slurry uniformity. In this regard, the literature within the last five years consistently underscores the significant advantage the continuous extruder holds over the batch mixer. One of the key findings being that continuous mixing can exert higher shear during mixing due to lower volume of process material. This results in lower viscosity, higher levels of de-agglomeration and generally a more processable rheology for cathode and anode slurries [37] [69]. Other studies emphasise the significance of a homogeneous distribution of shear imposed on all process material that passes through the continuous extruder, leading to better slurry uniformity and product quality consistency [46] [70]. Achieving consistency in shear for the entire volume of process material is vital for avoiding dead zones and maintaining slurry uniformity, but it is shown to be challenging to achieve in the larger volume of process material that passes through the planetary mixer [46].

4.2.4 Quality consistency and waste

As stated in [66], monitoring of slurry properties such as viscosity and density is essential for maintaining consistent slurry quality. It is described in [46] that the most practical method for evaluating slurry viscosity is currently through in-line pressure-differential measurements. More detailed viscosity curves, including both low- and high-shear viscosity, still require off-line measurements, according to the same article. Collecting the slurry samples needed for these analyses can cause temporary disruptions in a batch production process. It is also mentioned that in large-batch slurry production, it is often assumed that the small (≈20mL) sample is representative of the entire batch. As described in [46], this assumption may be reasonable over short time frames. However, it is also stated that due to the risk of sedimentation and agglomeration of active materials, the rheological properties of the slurry can shift over time, making small-sample measurements potentially unreliable for the actual batch. The article [46] reports that if a batch is found to be off-specification, it may result in the entire batch being discarded. Including the material lost during emptying and cleaning of batch mixers, the total material waste in the slurry preparation step in batch production corresponds to approximately 1% of the total slurry volume, according to the Research Associate interviewee [62].

In [46] it is noted that the issue of discarding entire batches can be avoided by transitioning from batch to continuous slurry processing. According to Rindi [62], the use of a twin-screw extruder can reduce material waste to approximately 0.1%. The interviewee also noted a slight decline in cell performance after prolonged production using the twin-screw extruder, although no apparent cause for this degradation has yet been identified.

It is also highlighted in [46] that the twin-screw extruder "necessitates continuous monitoring of the process and mapping of defect data", as the properties of the final slurry, such as density and viscosity, are highly dependent on the accuracy of the feeding system. The same article mentions that continuous mixing is not yet widely adopted, which creates a necessary learning phase for manufacturers to determine the optimal way to operate the continuous process. In contrast, the equipment supplier interviewed [63] states that the short residence time in the twin-screw leads to faster configuration time, compared to a planetary mixer, when the manufacturers are testing equipment for installation. However, the article [66] adds that, regardless of the mixing technology, the availability of process data is limited during the initial scaling of the production. The same article explains that while reliable process data is essential for optimising operations, such data can only be collected once production is already ongoing. Furthermore, the article notes that the absence of standardised protocols adds to the implementation challenges, as it increases the effort required to effectively integrate machinery and sensors. To address these challenges, the article [25] presents a strategy for implementing continuous anode slurry production using targeted data generation and AI-supported, model-based optimisation. It is stated that by combining prior process knowledge with a small number of strategically selected experiments, machine learning models can be trained effectively even under sparse data conditions. The article explains that this approach enables faster and more efficient process development by identifying essential correlations between process conditions and product characteristics without relying on extensive trial-and-error testing.

4.2.5 Production cost

Choosing between batch and continuous mixing processes will have a direct impact on production costs. Traditionally, batch mixing is associated with higher operational costs due to the fact that the production process is divided into distinct steps. In batch mixing, each batch requires separate preparation, processing, and cleaning. Each of these stages requires manual intervention, and because of that, it leads to the labor demands and total processing time per unit of output being increased.

Scaling the slurry mixing processes from a lab-scale to industrial scale presents economic challenges beyond the already discussed technical complexities. In batch systems, the non-linear scalability often results in, as mentioned earlier, the need to deploy multiple batch mixers in parallel to meet production targets [46]. Although this approach allows the scale of the total production volume of the slurry, it comes with raised operational costs due to higher labor demands, increased energy consumption, and increased floor space requirements [46]. These added costs, combined with the need for additional equipment, make scaled up batch-based systems less economically favourable for large scale production.

As previously outlined, continuous mixers streamline the production process by eliminating the stops required for batch processing. Economically, this leads to having shorter production cycles, reduced downtime and improved material utilisation, all of which improve throughput and lower per-unit manufacturing costs [46]. As continuous systems, such as the twin-screw extruder, are automated, they reduce the labour requirements, lowering labour costs per unit [6]. Additionally, by maintaining consistent slurry quality, the continuous process minimises material waste and quality-related rework [65]. Combined, these factors contribute to a more cost-effective and efficient production process.

When the two mixers, batch versus continuous, are compared directly to each other, there are, as already mentioned in the aforementioned paragraphs, several quantifiable differences in large-scale slurry mixing. As previously noted, a properly designed continuous mixing line can achieve significantly higher throughput than a planetary mixer [46]. Also shown earlier, in a facility with an annual output of 35 GWh, a continuous mixing system can achieve the same slurry production using only approximately 20% of mixers required in a comparable batch system [46]. Additionally, the continuous process reduces processing time. As mentioned earlier, slurry preparation time using a twin-screw extruder can be reduced from 120 minutes to 20 minutes [65]. These efficiencies improve throughput and also reduce labour, maintenance, and utility costs, demonstrating the long-term economic advantage of continuous mixing over traditional batch mixers.

According to [63], the number of operators needed for a continuous 125 mm line is 2.5. For a planetary mixer with a volume of 1500 L, one operator is needed per planetary mixer. Therefore, by using the assumption stated in the aforementioned paragraph, that six planetary mixers are needed to necessitate one continuous mixer, it would mean that the batch-based system would require six operators for the same output, compared to 2.5 operators needed for the continuous mixer. This results in a 58% reduction in labour costs for mixing using a continuous mixer.

The continuous process have shown to require 50% less solvent compared to what a batch mixer requires. For a batch mixer, the solvent content is approximately 40 wt%, for a continuous mixer it is reduced to 20 wt% [65]. As a result of this, the drying stage is reduced by 50%. According to [14], the drying stage is responsible for 46.84% of the energy consumption of electrode production. The reduction in drying time therefore results in substantial energy savings and lower per unit labour costs.

In terms of equipment footprint, continuous mixers offer an advantage in space efficiency over batch mixers. As previously mentioned, continuous mixers occupies approximately 30% less of the floorspace that would be needed for the planetary mixers [46]. According to the article, in production environments where slurry mixing occurs in dry rooms, a 30% reduction in space has a direct impact on energy consumption and operating cost linked to the drying room. For instance, designing a mixing line with 3 continuous mixers instead of 12 planetary mixers, while maintaining the same slurry output, can cut drying room energy use by up to 60% [46]. Bühler also mentions that the continuous mixer uses 56 kWh to produce 1 ton of slurry, while the planetary mixer uses 224 kWh to produce 1 ton of slurry [6]. These combined advantages underscore the energy and cost efficiency of continuous mixing systems over batch mixing systems.

However, when continuous mixing is implemented, there are different technical and economical considerations that the manufacturer must take into account. Technology is currently less established in the production of LIBs compared to batch mixing and therefore can involve additional engineering costs [46]. While continuous mixers lower long-term operating expenditures (OPEX), the initial capital expenditures (CAPEX) is typically more expensive [63].

When comparing the economical aspects in batch and continuous mixing, it is important to also compare the material waste the different techniques produce. Generally, batch mixing produces more waste because of the need for frequent cleaning between batches and variability in slurry quality. According to the supplier interviewee, Collins [63], the waste rates of a planetary mixer are approximately 0.2%, while a continuous mixer is reduced to approximately 0.05%. Furthermore, as mentioned in Quality consistency and waste, Rindi [62] confirms that continuous mixers produce less material waste compared to planetary mixers. Although the numbers differ, it can be concluded that continuous mixers improve material efficiency, which in turn reduces production costs.

4.2.6 Sustainability and environmental impact

As the transition to EVs is being accelerated by policies and market forces, the relevancy of continuous slurry mixing is increased. With production of EVs expected to rise substantially over the coming years, especially due to legislative actions such as the EU's planned ban on sales of vehicles with internal combustion engines by 2035 [71], the need for energy-efficient, ethical and scalable battery manufacturing processes becomes more urgent. Continuous mixing addresses these technical challenges as well as it aligns with emerging regulatory frameworks and industry trends that emphasise sustainability and ethical sourcing of raw materials. For example, there are different initiatives such as the European Green Deal that promote developments of supply chains that are low-emission, localised, and circular [72]. These objectives are met with continuous mixing through minimised material waste, lower energy consumption and compatibility with solvent-free processing. In the United States there are similar incentives in form of the Inflation Reduction Act [73]. It promotes the production of domestic battery components and ethical sourcing of critical materials. As a result, continuous slurry mixing offers a more efficient and sustainable alternative to batch mixing, better supporting the growing demands of lithium-ion battery production.

Neither planetary mixing nor continuous slurry mixing eliminates the use of cobalt or other critical elements. However, continuous mixing offers notable advantages in terms of better material efficiency and process control. For example, as noted earlier, for a twin screw extruder, the material loss is between 0.05% and 0.1% , which is less than the material waste produced from batch mixers, which is between 0.2% and 1% [62] [63]. When scaled to an industrial production scale, this efficiency can lead to substantial savings in NMC material each year, which itself leads to a reduction of demand for sensitive raw materials. Moreover, material utilisation, as mentioned above, is improved with continuous mixing by its ability to deliver more consistent slurry quality and reproducibility compared to batch mixing [65]. The twin screw extruder has an increased process stability and homogeneity which results in the final product having reduced variability, allowing for more precise formulation and efficient use of raw materials [46]. This results in minimising unnecessary waste being produced by using continuous mixer compared to batch mixer.

The direct environmental impact of LIB-NMC during use is relatively small. The indirect environmental impact is relatively minor as well, although it varies greatly depending on where in the world the battery is used and where the energy that is used to charge the battery comes from. For example, in Sweden one kWh of electricity emits approximately 41g of CO_2, while in China one kWh of electricity around 582g of CO_2, that is more than 14 times as much CO_2 per kWh[74]. The location where the cell is manufactured also plays a critical role in calculating the environmental impact of the cell's production, such as the emissions from energy usage. There are therefore many different factors that contributes to the total footprint of the of the battery over its entire lifecycle, which makes it hard to give a general answer to what the environmental impact of LIB-NMC is. In the article [75] it is mentioned how the carbon footprint differs depending on what production process is used for the materials used in a NMC. The article also shows that the majority of emissions originates from raw material extraction, 89% and 76% for battery with carbon-intesive materials and less carbon intensive materials respectively. Reducing material usage, for example by minimising waste and increasing the proportion of recycled materials could thus significantly reduce the environmental footprint of LIBs.

In addition to improving material efficiency, continuous mixing also contributes to a more sustainable battery manufacturing by enabling less use of solvent [65]. The use of solvent NMP brings certain risks. Some of the risks includes exposure of metal oxides as well as to the solvent NMP. NMP could cause reduced fertility, miscarriage and damage to liver and kidneys [76]. NMP is also harmful to the environment, as it is toxic to aquatic organisms. This has led to NMP being regulated within the EU and USA [76] [77].

In configurations where the solvent content is reduced or completely removed, energy demand for the electrode drying process is significantly reduced by implementing continuous mixing. As stated earlier, the drying process accounts for approximately 47% of the total energy consumption in electrode manufacturing [14]. Therefore, by using a continuous mixer, the need to recover the solvent can be minimised or eliminated, helping to lower greenhouse gas emissions, reducing hazardous solvents such as NMP and also reduce the carbon footprint of LIB manufacturing [65].

4.3 Adaptability to composition changes

Research for new and better batteries is ongoing. The twin-screw extruders ability to handle some of these changes is therefore relevant when it comes to how future-proof the equipment is. Thus, the following results state the adaptability of the twin-screw extruder to some of these possible changes, focusing on solvent-reduced and dry electrode manufacturing.

Solvent-reduced and solvent-free manufacturing is two promising ways to achieve a more ecological and economical sustainable production of LIBs [65] [78]. In solvent-reduced manufacturing, slurries with a lower amount of solvent and therefore a higher solids content compared to conventional slurries are used [79]. This makes the viscosity of the slurries much higher, minimising the drying time and, therefore, the energy consumption and the overall manufacturing cost. Dry electrode manufacturing has, on the other hand, totally eliminated the solvent. This means that active materials, conductive additives and binders are mixed in their solid-state powder form [80]. The mixture can then be applied directly to the collector, completely eliminating the manufacturing steps for solvent recovery and drying [81].

4.3.1 Solvent-reduced electrode manufacturing

Studies show that the twin-screw extruder can handle compositions with 50% less solvent than the conventional slurry made with a planetary mixer [65] [79]. Dreger et al. [65] compared, among other things, the production of diluted (60wt% solid mass content) and solvent-reduced (75wt% solid mass content) NMC cathodes in a laboratory-scaled twin-screw extruder. There were no significant differences determined, except that the constant drying time was reduced by half when using 50% less solvent (NMP). This made a higher production capacity possible, while using a dryer with the same length. The adhesion strength of the extruded cathodes was also determined to be equal to or even slightly better than the reference values. Overall, the extruded cathodes showed improved electrochemical properties, partly due to the strong de-agglomeration that resulted in a finer electrode structure.

In a laboratory study by Wiegmann, Kwade, and Haselrieder on solvent-reduced anode slurrys graphite anodes with ionized water as solvent and a solids mass content of 76.5wt% were prepared in a twin-screw extruder. With the twin-screw extruder, granulates were created and then fed into the calendering machine. A continuous calendering step and short-time drying process (with an IR-radiator field) could then be achieved (see figure 7). This was argued to have the ability to simplify the production, by combining steps, and to reduce energy related costs due to a shorter drying time and in the case of cathodes, less need for NMP recovery.

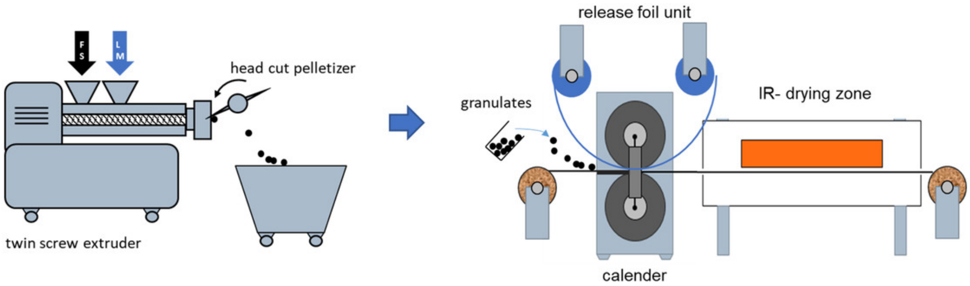

Figure 7: A laboratory setup of a solvent-reduced process. Used according with permission from publisher [79].

In the same study by Wiegmann, Kwade, and Haselrieder, the twin-screw extruder was found to exsert a high power input on the mixed materials [79]. This led to high shear stresses that could create structural changes to the ingoing components of the anode. To reduce the shear stresses and torque on the particles, the extruder was heated to 60°to improve the wetting ability of the solvent (ionized water). However, it was found that not all binders could create sufficient adhesion between the coating and the substrate. This was, for instance, the case for the conventionally used CMC/SBR-binder (for anode production) used as reference. Instead, a formulation of a nitrile rubber-polymer (NBR) in powder form was found adequate. When made into pouch cells, it was able to compare to the reference when it comes to cycling stability and even slightly surpass it when it comes to absolute capacity. The powdered NBR was also lighter and therefore argued to be easier to transport and store. Extruded granulates were also found to be better for longer storage (at least a month) compared to the commercial low viscosity slurry. This was because the high solid content in the granulates prevented them from being affected by sedimentation effects, when sealed in an airtight bag.

A follow up study, made by Wiegmann, Cavers, Diener, and Kwade, of solvent-reduced extrusion of the anode electrode found that structural and morphological changes occur due to the high specific power input on the mixture [78]. In this study, the high viscosity slurries was produced with three different screw configurations and compared to a planetary mixer with a conventional low viscosity slurry as a reference. The screw configuration was found to influence the residence time of the mixture in the extruder, although all configurations had much shorter residence times (under 5 minutes) compared to the reference (60 minutes). It was also found that the specific power input in the extrusion processes is much higher than in the reference case because of the higher solids content. The specific power input was also influenced by the screw configuration. Higher power input was, for example, related to a higher surface area on the produced anode, where both a too large and a too small surface area lead to a higher ionic resistance. Therefore, it was concluded that the screw configuration is important when finding the balance between the electrode structure and the electrochemical performance of the finished cell with solvent-reduced extrusion.

4.3.2 Dry electrode manufacturing

Solvent-free or dry electrode manufacturing is a fairly new technique that still has its challenges, but shows a lot of potential when it comes to, for example, increasing efficiency and lowering environmental impact [82] [83]. Dry electrode manufacturing with a twin-screw extruder is possible in a process called melt extrusion. In this process, the temperature of the mixture gradually increases as it passes through the extruder. This makes the binder slowly melt, resulting in an even and secure adhesion between the conductive additives and the active materials [83]. Heat can also be generated due to the high shear forces that occur when mixing dry substances [81]. The mixture is then extruded through a die opening, creating a cohesive film with the desired thickness. The film is then applied to the current collector. This method therefore puts different requirements on the binder of choice, compared to the solvent case [83].

Another emerging solvent-free technique is the 3D printing method of fused deposition modeling, also called fused filament manufacturing [83]. In this technique, an extruder creates the filament that is then fused onto the electrodes. With this 3D technology, the electrode is created one layer at a time, giving precise control over the structure and thickness. In a study on 3D printing cathodes, researchers used solvent-free mixing with a twin-screw extruder to create its filaments for the 3D printer [84]. There, working filaments of formulations with Lithium Iron Phosphate (LFP), as active material and Carbon Nanofibres (CNF) as conductive additive were derived. A 10 h pre-mixing of the LFP and CNF powders took place before the extrusion process. The filaments were first created on a laboratory scale, and then one of the filaments was produced in a larger extruder using the same method. There, the filament from the upscaled method had about 9 times higher electronic conductivity compared to its laboratory scaled filament. Therefore, it was concluded that this showed promising results for use in industrial manufacturing with that specific formulation.

4.4 Insights on the current discord on industrial mixing standard

Interviews with representatives from research institutions, equipment suppliers, and battery manufacturers were conducted. This gained insight into why planetary mixers are still considered the industry standard in battery manufacturing, despite the documented advantages of twin-screw extruders and their established use as a standard in other industries. The interviewees offered different perspectives, providing a diverse view of the current state of the potential transition from batch to continuous mixing, and the challenges associated with establishing new industrial standards.

During the interview with Martin Karlsson [61], previous University Relations Manager at Northvolt, he explained that in the projects he has been involved in, continuous mixing had never been considered for implementation. This highlights a perception that twin-screw extrusion is not yet widely recognised as a viable alternative to the current batch-based manufacturing process by the manufacturers. Nonetheless, Karlsson expressed optimism about the potential of continuous mixing, particularly in light of the growing need to optimise production within future LIB gigafactories to meet increasing battery demand. He also noted a general lack of expertise in battery manufacturing within public research, particularly at Swedish universities, but also to some extent across Europe. According to Karlsson, this area has not been sufficiently prioritised within publicly funded research efforts, which he sees as a limiting factor for industrial development in Europe.

When asked about if companies are considering continuous mixers, the researcher Carola Rindi from Fraunhofer FFB mentions in an interview that manufacturers are not doing it as of today regarding battery manufacturing [62]. Rindi thinks that researchers has to publish more about this technique to show companies that it works and is beneficial. The leading marketers such as China and USA all use batch mixers since the continuous alternative is not as known [62].

According to Rindi, companies are not innovative enough and a main factor is yet again the lack of research that shows that a continuous mixer can produce better results than that of a batch mixer [62].

For Rindi the hope is that companies will want to move away from batch mixers because of the potential that the continuous mixer inherit. Companies might also be too scared of this transition due to the unknown grounds regarding this technique in battery manufacturing and not ready to try something that could be unsuccessful and involves a lot of money [62].

During the interview with the Area Sales Manager at Bühler, Dave Collins, it was presented a different point of view compared to what Carola Rindi and Martin Karlsson stated. According to Collins the demand and interest of continuous slurry mixing lines is high due to an increased awareness of sustainability and companies have had to adapt. Companies has been forced to think differently and move away from thinking that batch is the only way to produce LIBs to consider a different continuous mixing line technique. However, challenging market conditions currently exist for battery manufacturers [63].

Key points that, according to Collins, benefits the continuous mixer over the traditional batch mixer are scale of economy, energy consumption, labour and material losses. When asked more about the economical point of view, Collins states that this type of transition is more adopted to a gigafactory and less feasible for smaller companies since factors such as the CAPEX of the mixers are high. What makes this transition doable with bigger factories is that the OPEX quickly offset the initial investment of the mixers [63].

The type of customers that uses Bühler's products varies all the way from researchers that will want to use a pilot or lab scale operation, to a full on production plant cell manufacturer [63]. According to Collins the customers also varies from new battery manufacturers to companies wishing to expand their already existing production [63]. Collins also mentions that existing companies that uses batch mixing lines are not looking to swap them out, rather to expand their production with the continuous mixers [63]. The location of the companies that contact out to Bühler also varies, Bühler has fulfilled over 80 continuous mixing lines across Asia, Europe, and North America.

Rindi mentions that there are not many differences in the product of the different process techniques. Although using the same recipe there was lower viscosity for the batch mixer. The viscosity of the slurry is a vital part when it is transported onto the coating process [62]. Rindi and her research team could also see that the particles was better and the slurry was more homogeneous with the continuous mixer. If the particles in the slurry is to big, talking merely in micrometers, it causes problems with the electrodes and the ions that flow through the cell [62].

When asked about the time a production line can be implemented, Collins answered that for a gigafactory scale, it takes about 3-6 months from order/contract to deliveries, another 3-4 months of factory testing, deliveries to sites and installation, after that a further 3 months for dry and wet commissioning, site acceptance testing, initial product, staff training and handovers for a combined time of around 13 months from order to a running production line [63].

By the end of each interview with Rindi and Collins, they were asked if continuous mixing is the future in battery manufacturing. Rindi states that, if considering the advantages, the answer is yes. Although it will, of course, follow some challenges with it. In her opinion it is the researchers role to make this possible by producing results in order to be able to implement continuous mixers into battery manufacturing [62]. Collins also answered that the technique indeed is the future, but that it is already here and companies are aware of the technique [63].

5 Discussion

In the discussion, the results and methods will be analysed and reviewed. An outlook will be conducted to explore the future potential of continuous mixing in battery manufacturing and identify areas for further research. This section aims to place the findings in a broader industrial and research context.

5.1 Methodology discussion

In this section, potential limitations of the chosen methodology will be discussed. First, the process of the literature review will be examined, evaluating its scope and approach. Following that, the chosen interview participants will be discussed, considering how their backgrounds and views might have influenced the findings.

5.1.1 Literature review

One of the main limitations of the literature review was the low number of publicly available academic publications identified on the topic of continuous slurry mixing. This may be due to the fact that the technology is still fairly new or that much of the development is conducted in-house by companies and not shared through academic channels, which limits the scope of publicly accessible knowledge. Furthermore, no formal review protocol was used during the literature review, which may have introduced inconsistencies in the selection process and increased the risk of missing potentially relevant sources. A systematic and documented search strategy would have improved both transparency and reproducibility.

Another limitation of the review is the exclusive focus on publications in English. Given that much of the development and implementation of continuous mixing technology is taking place in East Asia, relevant research published in languages such as Chinese, Korean, or Japanese may have been overlooked. This introduces a geographic and linguistic bias that could affect the comprehensiveness of the review. These limitations suggest that while the literature review provided valuable insights, it may not fully capture the global state of research and industrial practice. Future studies would benefit from a broader, multilingual search strategy and the use of a systematic protocol to ensure a more comprehensive overview.

Regarding the publication dates of the reviewed articles, the inclusion criteria were set to the past 15 years. However, particular emphasis was placed on sources published within the last five years, due to the rapid technological developments in the field. Older publications were still included when they provided relevant insights into slurry quality and formulations that had been successfully achieved using twin-screw extrusion.

5.1.2 Interviews

The interview questions were tailored to each participant's professional role in order to provide relevant and in-depth insights. As previously described, this role-based approach aimed to ensure that each interview contributed uniquely to the research questions. Martin Karlsson, former University Relations Manager at Northvolt, was posed with questions focusing on how manufacturers evaluate new production technologies, such as mixing equipment. Since he held this position until recently, it is unlikely that significant changes in manufacturer attitudes toward continuous mixing have occurred in the short time since. However, a gradual shift in awareness cannot be ruled out.

The questions directed to Carola Rindi, researcher at Fraunhofer FFB, centered on ongoing research activities and technical findings related to twin-screw extrusion. Her input was valuable for understanding how continuous mixing is studied and optimized within the academic context, particularly in comparison to conventional batch processing using planetary mixers. Similar technical questions were asked to Dave Collins, Area Sales Manager at Bühler. In addition to discussing process characteristics, he was also asked about the maturity of their technology and its commercial interest. While his role as a supplier representative means that some degree of promotional bias must be considered, his responses still served as a relevant technical reference and provided a unique industry-side perspective on market readiness. At the same time, the supplier's viewpoint is essential for understanding the commercial status of twin-screw extruders in battery manufacturing. Clarifying whether the twin-screw extruders for battery slurry are already in operation or remain in the development phase. This perspective complements the research and manufacturing views by providing insight into adoption trends and customer demand.

5.2 Result discussion

In this section, the results related to the research question will be analysed and discussed in detail. The discussion will focus on interpreting the key findings in relation to the advantages and challenges of both continuous and batch mixing systems. Additionally, the standardisation of mixing technologies will be explored, particularly in terms of its potential to streamline processes and enhance efficiency. Finally, the implications of future LIB components and formulations will be examined in relation to the adoption of the twin-screw extruder, considering how evolving technologies could shape the industry's approach to slurry mixing.

5.2.1 Comparison discussion

It becomes apparent that continuous mixing is regarded as a promising alternative to batch processing for battery slurry production, offering potential benefits in terms of efficiency, scalability, sustainability, slurry consistency, and process control. The primary challenges associated with implementing twin-screw extruders include the high initial investment cost, the difficulty of switching slurry components without thorough cleaning, and the absence of standardised production protocols. Research Associate Carola Rindi, mentioned a slight decline in cell quality after prolonged production using the twin-screw extruder. However, as the underlying cause of this result was not clearly identified, it highlights the need for continued research to better understand and optimise the technology.

It is worth noting that the lack of quantifiable data also poses a challenge when evaluating the performance of planetary mixers. That said, one advantage of batch processes is the broader industry expertise and more established process design. This can facilitate implementation and operation compared to the twin-screw extruder, despite the absence of standard protocols for either mixer technology. At the same time, it is important to note that twin-screw extrusion for battery slurry is no longer in a development phase, as several suppliers now offer full-scale production systems, making it a viable alternative to the planetary mixer.

The number of accessible articles on continuous slurry mixing is limited, as observed in the literature review presented in the results. Moreover, the available sources primarily describe the opportunities and challenges in general terms, without providing detailed quantifications of the required process parameters or performance metrics. Continuous mixing is known to provide reduced energy consumption, smaller required floor space, and fewer mixers compared to batch processing. However, such claims are only occasionally supported by numerical data, and often lack in-depth analysis or standardised comparisons or are only provided by suppliers. This lack of detail makes it difficult to quantify the performance differences between continuous and batch mixing, thereby complicating objective evaluations and informed decision-making.

5.2.2 Future battery technologies

Slurry mixing in the twin-screw extruder is possible not only with the same composition of solid mass content and solvent as that of the conventional slurry but also with lower amounts of solvent with promising results. For both the anode and the cathode, the amount of solvent could be reduced by 50%, resulting in shorter drying times that can minimise energy consumption and environmental impact.

Solvent-reduced extrusion could thus make the steps of calendering and drying more continuous, making the whole production less complicated and more effective. Another advantage of solvent-reduced extrusion is the longer storage time. Granulates can then be saved for later when there is a temporary halt in the production. The longer storage can also be used for transporting granulates longer distances, making trading easier. However, it should be noted that one of the studies on the anode ([78]) was a follow-up study of the other article presented regarding the anode ([79]). This, as well as one author being present in all three of the presented studies ([65], [78], [79]), creates the risk that the studies are somewhat partial. However, it also excludes too much of overlapping between the studies.

Dry electrode manufacturing was found to be a promising new alternative for more sustainable battery production. This production eliminates the steps for drying and solvent recovery. Therefore, it also eliminates the risk of solvent emissions, which otherwise could have caused potential harm to personnel and environment. However, the composition still needs more research to create optimal electrodes. The possibility of using 3D technology to create precise dry electrodes has a lot of potential when it comes to creating complicated electrode structures. This can be relevant in the future when other types of more complex battery cells might be needed. Even in this future, the twin-screw extruder has its place creating the filaments for the 3D printer using dry extrusion.

In both solvent-reduced and solvent-free manufacturing, not all binders were found suitable. This was mainly due to the high shear forces exerted by the twin-screw extruder.A switch from a planetary mixer to a solvent-reduced/free manufacturing with a twin-screw extruder can therefore be argued to require careful studies of how the specific electrodes are affected by the high shear forces. However, the twin-screw extruder is modular, with results pointing to that the choice of screw configuration greatly influences the shear forces. Thus, one can argue that the extruder is a versatile equipment, able to handle different materials and compositions. This would suggest that the twin-screw extruder is a suitable equipment even if future LIBs change its formula.

The results concerning changes in LIB composition suggest that the twin-screw extruder is not merely a suitable option to accommodate future advancements, but rather that its implementation is increasingly regarded as a necessity for these developments. These future components are being developed with the goal of reducing the production footprint, while maintaining or even enhancing cell performance. In parallel, manufacturers aim to position themselves as more sustainable alternatives, driven not only by environmental ambitions but also by the increasing regulatory demands placed on the battery industry. These demands also include improved energy efficiency, an area where the twin-screw extruder has demonstrated advantages over the planetary mixer. Despite the limited expertise and lack of standardised protocols, the transition to continuous mixing appears inevitable in light of these environmental considerations.

5.2.3 Standardisation discussion

Based on the results presented in section 4 Results, it has been shown that continuous extrusion holds a considerable advantage in most of the parameters used to compare the two mixing methods. Even though, we have gained great insight into the companies that utilise the twin-screw extruder through our interviews. It is still unclear as to why continuous slurry processing is not an industrial standard, considering the studied benefits, this is the basis for discussion in the following section.

One potential contributing factor is that all the literature in the subject uses lab/pilot-scale equipment. Although these studies generally agree on the benefits of continuous slurry mixing, they do not address potential issues that may arise when ramping up to industrial-scale continuous slurry mixing for LIBs. The lack of studies replicating lab-scale results on industrial-scale systems leaves gaps in the literature as to how factors like slurry rheology, material flow and energy consumption deviate from the lab-scale experiments. Therefore, this lack of data on the twin-screw extruder on an industrial scale introduces uncertainties for a potential manufacturer in Europe when deciding on industrial mixing systems. Furthermore, it is unclear whether this gap in the literature is due to the inability of academical studies to replicate industry-scale environments or the unwillingness of companies within the industry to share data on the industrial-scale performance of the twin screw extruder. As reported by a Bühler representative [63], many of the companies that utilise their twin screw extruder are located in Asia; this indicates that continuous slurry mixing is clearly feasible on an industrial scale, but the data and expertise are concentrated in Asia. This further reflects the competitive advantage that Asian (mostly Chinese) companies hold over their European counterparts within the industry, and can perhaps be seen as a roadmap for the future of European battery manufacturing.

When conducting the interviews with all three candidates, one can indicate contradictions between candidates. From a researcher and manufacturers point of view, battery manufacturers are not aware of the possibilities and potential that a continuous mixing line inherit, the lack of research and geographic location are arguments as to why this could be, by geographic location it is depending on the different research and knowledge from companies in i.e Europe or Asia. However, when asked for a suppliers point of view, the opposite is stated, that manufacturers are aware of the technique and are using it as of today.

From the different interviews, one can conclude that if companies would want to expand their production with continuous mixers although they might use batch mixing equipment, it wouldn't be a problem, since the results of each technique were similar according to Rindi [62]. All parties pointed in the same direction that continuous mixing lines in battery manufacturing process is the future in the field. The only contradiction is, once again, that the researchers and suppliers have different views. Rindi thinks that the technique is not here yet, some might be using it, but mostly on a pilot scale and not so much on a bigger scale, whilst suppliers claim that manufacturers are using it already.

The implementation of a continuous mixing line is also, according to Collins [63], a process of roughly 19 months. This estimate timeline could vary depending on where the mixing line is to be shipped. With respect to the implementation time alone, it is not the deciding factor regarding the choice of the mixing system.

5.2.4 Sustainability impact

Democratic Republic of Congo accounts for about 70% of the world's cobalt extraction[85]. It is also stated that around 45% of the cobalt extracted is used solely for manufacture batteries used in EVs. obalt mining in DRC has been associated with numerous ethical questionable topics such as human right violations, child labour and corruption. As discussed in Production volume, the twin-screw extruder offers a significantly higher production capacity compared to the planetary mixer. Implementing the twin-screw extruder as the industrial standard would therefore likely lead to a global increase in the production of LIBs, potentially worsening the already existing problems with mining in the Democratic Republic of Congo. However, change could be driven from growing international attention and economic importance placed on these critical minerals. For example, the EU has introduced the EU Battery Regulation [86], which enforces stricter ethical sourcing standards. The regulation aims to enhance transparency and ensure that materials used in battery manufacturing are sourced responsibly. In the article [87] it is shown how the mining industry in DRC is relatively acceptable of changes leading to more ethically sustainable mining.

In Sustainability and environmental impact, it is mentioned that new laws are being implemented to steer the market toward a green transition. Historically, such regulations have generally become increasingly strict over time, making it reasonable to assume that this trend will continue. Future legislation is therefore likely to further affect areas such as energy consumption and the emission of harmful chemicals such as NMP. These restrictions could enhance the viability of the twin-screw extruder, as it offers lower energy consumption compared to planetary mixers and is compatible with dry mixing.

The twin-screw extruder system could provide more frequent and consistent monitoring of the electrode slurry compared to a planetary mixer. This capability makes it potentially more suitable for processing recycled materials, which often exhibit lower and more variable quality than newly processed raw materials, factors that can significantly affect slurry quality. By analysing slurry characteristics in real time, the twin-screw extruder could potentially adjust input parameters accordingly, helping to compensate for the inconsistencies inherent in recycled materials. Increasing the use of recycled materials would save costs and reduce the environmental impact.

5.2.5 Future work

Although this work highlights the advantages of continuous slurry mixing in LIB manufacturing, several avenues remain for future research. First, the amount of data available on twin-screw extruders and their comparison to planetary mixers is relatively limited, with most existing data originating from laboratory settings or pilot-scale facilities. Therefore, more data must be collected and publicly presented to ensure more reliable and general results. Large-scale industrial trials are necessary to evaluate and validate laboratory findings under real production conditions.

Since continuous slurry mixing in LIB manufacturing is a relatively new concept, long-term effects and performance data are not yet available. Therefore, aspects such as the long-term reliability of the process and equipment wear remain uncertain and require further investigation. These results would also be helpful in an environmental impact assessment comparing twin-screw extruders and planetary mixers, which would provide a clearer understanding of which option is more environmentally sustainable.

More research could also be applied to investigate the compatibility between continuous mixing, particularly the twin screw extruder, and future batteries compositions and manufacturing techniques, such as dry mixing, silicone based anodes and infrared drying. Providing valuable information for the future of LIB manufacturing.

Finally, more interviews, particularly with someone responsible for developing new large-scale production lines for LIB manufacturing, would provide valuable insight into if the twin screw extruder is considered in the manufacturing design, and why that would be the case.

6 Conclusion

In conclusion, this study aimed to evaluate the potential of transitioning from batch mixers to continuous mixers in lithium-ion battery manufacturing. The results show that the twin-screw extruder, offers several advantages over the batch mixer, such as better slurry homogeneity, lower energy consumption, less waste, and improved scalability. These findings highlight the relevance of continuous mixing as the battery industry are facing growing production demand and sustainability challenges.

However, despite the advantages the continuous mixer offers, the report identifies numerous reasons why continuous mixing has not yet been widely implemented in the industry. One of the barriers is the lack of publicly available, large-scale quantitative data of continuous mixing in industrial environments. This gap in publicly accessible information makes it difficult to fully assess its advantages across different manufacturing settings. Additionally, the analysis highlights the higher initial investment cost of the twin-screw extruder in comparison to the conventional planetary mixers. Furthermore, interviews conducted with industry experts also reveal a lack of awareness from manufacturers regarding continuous slurry mixing. This is particularly evident in Europe, where the technology has seen limited adoption compared to countries such as China, where it has been implemented at a larger extent.

Nevertheless, for the future of battery manufacturing, continuous mixing remains a promising solution. In particular, it is well suited for the demands large-scale industries set as well as for emerging battery technologies, such as dry electrode and solvent-reduced/-free manufacturing. The relevance of these methods increases as usage of toxic solvents such as NMP could become more regulated, and as manufacturers search for cleaner, more cost-effective production strategies.

This study concludes that continuous mixing is a viable alternative to traditional batch mixing in LIB manufacturing. For continuous mixing to become more widely implemented in the industry, greater access to industrial-scale performance data and increased industry awareness will be essential. With further research, better collaboration between manufacturers, equipment suppliers, and researchers, continuous mixing has the potential to play a key role in making battery production more efficient, scalable, and sustainable.

References

[1] International Energy Agency, *Status of battery demand and supply*, `https://www.iea.org/reports/batteries-and-secure-energy-transitions/status-of-battery-demand-and-supply`, Part of the report: Batteries and Secure Energy Transitions, Apr. 2024. (visited on 05/12/2025).

[2] M. I. Khan, R. Gilani, J. Hafeez, R. Ayoub, I. Zahoor, and G. Saira, "Chapter 3 - Advantages and disadvantages of lithium-ion batteries", in *Nanostructured Lithium-ion Battery Materials*, S. Thomas, A. B. Gueye, O. Savadogo, and H. J. Maria, Eds., Elsevier, 2024, pp. 47–64, ISBN: 9780443133381. DOI: `10.1016/B978-0-443-13338-1.00017-4`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/B9780443133381000174` (visited on 02/14/2025).

[3] R. Udendhran, T. R. Mohan, B. R, *et al.*, "Transitioning to sustainable e-vehicle systems – global perspectives on the challenges, policies, and opportunities", *Journal of Hazardous Materials Advances*, vol. 17, p. 100 619, 2025, Accessed 11 May 2025. DOI: `https://doi.org/10.1016/j.hazadv.2025.100619`. [Online]. Available: `http://sciencedirect.com/science/article/pii/S2772416625000312?via%3Dihub` (visited on 05/11/2025).

[4] EY Global, *EY announces 9 key recommendations to boost investment and make Europe more competitive*, Jun. 2024. [Online]. Available: `https://www.ey.com/en_gl/newsroom/2024/06/global-auto-industry-paradigm-shift-driving-us-660b-transformation-opportunity-ey-value-pools-analysis` (visited on 03/03/2025).

[5] Volta Foundation, "Optimizing mixing processes for battery electrode slurries: Key techniques and considerations", *Battery Bits*, Dec. 2024. [Online]. Available: `https://volta.foundation/battery-bits/optimizing-mixing-processes-for-battery-electrode-slurries`.

[6] Bühler, *Efficient continuous electrode slurry production.* [Online]. Available: `https://www.buhlergroup.com/global/en/industries/batteries/Continuous-electrode-slurry-production.html` (visited on 04/20/2025).

[7] *Battery university*, Sep. 2010. [Online]. Available: `https://batteryuniversity.com/article/bu-204-how-do-lithium-batteries-work` (visited on 05/12/2025).

[8] *Ul research*, Sep. 2021. [Online]. Available: `https://ul.org/research-updates/what-are-lithium-ion-batteries/` (visited on 05/12/2025).

[9] P. M. Tembo, C. Dyer, and V. Subramanian, "Lithium-ion battery recycling—a review of the material supply and policy infrastructure", *NPG Asia Materials*, vol. 16, no. 1, p. 43, Aug. 2024, ISSN: 1884-4057. DOI: `10.1038/s41427-024-00562-8`. [Online]. Available: `https://www.nature.com/articles/s41427-024-00562-8` (visited on 05/12/2025).

[10] M. Kotal, S. Jakhar, S. Roy, and H. K. Sharma, "Cathode materials for rechargeable lithium batteries: Recent progress and future prospects", *Journal of Energy Storage*, vol. 47, Mar. 2022, ISSN: 2352-152X. DOI: `10.1016/j.est.2021.103534`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2352152X21012159` (visited on 03/05/2025).

[11] Dragonfly Energy, *A Guide To The 6 Main Types Of Lithium Batteries*, Dec. 2022. [Online]. Available: `https://dragonflyenergy.com/types-of-lithium-batteries-guide/` (visited on 03/05/2025).

[12] A. K. Koech, G. Mwandila, F. Mulolani, and P. Mwaanga, "Lithium-ion battery fundamentals and exploration of cathode materials: A review", *South African Journal of Chemical Engineering*, vol. 50, pp. 321–339, Oct. 2024, ISSN: 1026-9185. DOI: `10.1016/j.sajce.2024.09.008`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S1026918524001100` (visited on 02/14/2025).

[13] Automotive Manufacturing Solutions, *Powering the future: Top 5 EV battery chemistries and formats across the world*, Jul. 2024. [Online]. Available: `https://www.automotivemanufacturingsolutions.com/top-5-ev-battery-chemistries-and-formats-across-the-world/45901.article` (visited on 03/05/2025).

[14] Y. Liu, R. Zhang, J. Wang, and Y. Wang, “Current and future lithium-ion battery manufacturing”, *iScience*, vol. 24, no. 4, p. 102 332, Apr. 2021, ISSN: 2589-0042. DOI: `10.1016/j.isci.2021.102332`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S258900422100300X` (visited on 03/04/2025).

[15] Aqua Metals, *What Are Battery Anode and Cathode Materials?*, Apr. 2023. [Online]. Available: `https://www.aquametals.com/recyclopedia/lithium-ion-anode-and-cathode-materials/` (visited on 05/11/2025).

[16] H. Zhang, Y. Yang, D. Ren, L. Wang, and X. He, “Graphite as anode materials: Fundamental mechanism, recent progress and advances”, *Energy Storage Materials*, vol. 36, pp. 147–170, Apr. 2021, ISSN: 2405-8297. DOI: `10.1016/j.ensm.2020.12.027`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2405829720304906` (visited on 05/11/2025).

[17] P. U. Nzereogu, A. D. Omah, F. I. Ezema, E. I. Iwuoha, and A. C. Nwanya, “Anode materials for lithium-ion batteries: A review”, *Applied Surface Science Advances*, vol. 9, p. 100 233, Jun. 2022, ISSN: 2666-5239. DOI: `10.1016/j.apsadv.2022.100233`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2666523922000253` (visited on 05/11/2025).

[18] X. Yi, G. Qi, X. Liu, C. Depcik, and L. Liu, “Challenges and strategies toward anode materials with different lithium storage mechanisms for rechargeable lithium batteries”, *Journal of Energy Storage*, vol. 95, p. 112 480, Aug. 2024, ISSN: 2352-152X. DOI: `10.1016/j.est.2024.112480`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2352152X24020668` (visited on 05/11/2025).

[19] T. Shen, Z. Yao, X. Xia, X. Wang, C. Gu, and J. Tu, “Rationally Designed Silicon Nanostructures as Anode Material for Lithium-Ion Batteries”, *Advanced Engineering Materials*, vol. 20, no. 1, p. 1 700 591, Jan. 2018, ISSN: 1438-1656, 1527-2648. DOI: `10.1002/adem.201700591`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/adem.201700591` (visited on 05/11/2025).

[20] R. Miyazaki, “High-Capacity Anode Materials for All-Solid-State Lithium Batteries”, *Frontiers in Energy Research*, vol. 8, Aug. 2020, ISSN: 2296-598X. DOI: `10.3389/fenrg.2020.00171`. [Online]. Available: `https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2020.00171/full` (visited on 05/11/2025).

[21] L. Zhao, S. Wang, X. Liu, W. Quan, J. Zhang, and J. Li, “PNb9O25-Li4Ti5O12 blended anode with enhanced capacity and volumetric energy density”, *Applied Surface Science*, vol. 685, p. 162 031, Mar. 2025, ISSN: 0169-4332. DOI: `10.1016/j.apsusc.2024.162031`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0169433224027478` (visited on 05/11/2025).

[22] Elsevier, *Scopus preview - Scopus*, 2025. [Online]. Available: `https://www.scopus.com/home.uri` (visited on 05/11/2025).

[23] T. Liu and F. Gao, “Batch process control”, in *Industrial Process Identification and Control Design: Step-test and Relay-experiment-based Methods*, London: Springer, Oct. 2012, pp. 433–452, ISBN: 9780857299772. DOI: `10.1007/978-0-85729-977-2_12`. [Online]. Available: `https://doi.org/10.1007/978-0-85729-977-2_12` (visited on 03/04/2025).

[24] A. C. Dimian, C. S. Bildea, and A. A. Kiss, “Chapter 11 - Batch Processes”, in *Integrated Design and Simulation of Chemical Processes*, ser. Computer Aided Chemical Engineering, vol. 35, Elsevier, 2014, pp. 449–488. DOI: `https://doi.org/10.1016/B978-0-444-62700-1.00011-5`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/B9780444627001000115` (visited on 02/27/2025).

[25] S. Oberdiek, L. Jalowy, F. G. Vazquez, M. Risling, and K. Wahl, “Targeted Data Generation in the Continuous Production of Anode Slurries for Lithium-Ion Battery Cells”, in *2024 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)*, ISSN: 2831-6983, Mar. 2024, pp. 558–562. DOI: `10.1109/ICAIIC60209.2024.10463350`. [Online]. Available: `https://ieeexplore.ieee.org/document/10463350` (visited on 04/07/2025).

[26] W.-C. Chen, P.-D. Lee, C.-H. Ni, *et al.*, “Flowing to purity: Advancing acetylsalicylic acid production from batch to continuous to full-flow”, *Separation and Purification Technology*, vol. 369, Oct. 2025, ISSN: 1383-5866. DOI: `10.1016/j.seppur.2025.133107`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S1383586625017046`.

[27] Lindor, *Continuous Mixing Made Simple: What You Need to Know.* [Online]. Available: `https://lindor.nl/article/continuous-mixing-made-simple-what-you-need-to-know/` (visited on 05/11/2025).

[28] J. Staggert, *Batch vs Continuous Manufacturing of Battery Electrode Slurry*, Jun. 2023. [Online]. Available: `https://www.thermofisher.com/blog/materials/batch-vs-continuous-manufacturing-of-battery-electrode-slurry/` (visited on 02/23/2025).

[29] C. D. Reynolds, H. Walker, A. Mahgoub, E. Adebayo, and E. Kendrick, “Battery electrode slurry rheology and its impact on manufacturing”, *Energy Advances*, vol. 4, no. 1, pp. 84–93, Jan. 2025, ISSN: 2753-1457. DOI: `10.1039/D4YA00380B`. [Online]. Available: `https://pubs.rsc.org/en/content/articlelanding/2025/ya/d4ya00380b` (visited on 02/17/2025).

[30] R. Krishnan and G. Gopan, “A comprehensive review of lithium extraction: From historical perspectives to emerging technologies, storage, and environmental considerations”, *Cleaner Engineering and Technology*, vol. 20, p. 100 749, Jun. 2024, ISSN: 2666-7908. DOI: `10.1016/j.clet.2024.100749`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2666790824000296` (visited on 03/18/2025).

[31] N. Faris, A. J. Fischmann, S. Assmann, *et al.*, “A study into the behaviour of nickel, cobalt and metal impurities during partial neutralisation of synthetic nickel laterite pressure leach solutions and pulps”, *Hydrometallurgy*, vol. 202, p. 105 604, Jun. 2021, ISSN: 0304-386X. DOI: `10.1016/j.hydromet.2021.105604`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0304386X21000530` (visited on 03/18/2025).

[32] Cobalt Institute, *Cobalt mining*, Accessed 11 May 2025, 2025. [Online]. Available: `https://www.cobaltinstitute.org/about-cobalt/cobalt-life-cycle/cobalt-mining/` (visited on 05/11/2025).

[33] Wilson Center, *The DRC Mining Industry: Child Labor and Formalization of Small-Scale Mining — Wilson Center*, Mar. 2025. [Online]. Available: `https://www.wilsoncenter.org/blog-post/drc-mining-industry-child-labor-and-formalization-small-scale-mining` (visited on 03/18/2025).

[34] B. B. Nayak and S. K. Mishra, “Review on manganese ore deposits and prospect in india with special reference to odisha – a geological perspective”, *Journal of Ecology and Environmental Science*, vol. 6, no. 2, pp. 138–143, 2024, Accessed 11 May 2025. [Online]. Available: `https://www.ecologyjournal.in/assets/archives/2024/vol6issue2/6016.pdf` (visited on 05/11/2025).

[35] K. Konda, S. B. Moodakare, P. L. Kumar, *et al.*, “Comprehensive effort on electrode slurry preparation for better electrochemical performance of LiFePO4 battery”, *Journal of Power Sources*, vol. 480, p. 228 837, Dec. 2020, ISSN: 0378-7753. DOI: `10.1016/j.jpowsour.2020.228837`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0378775320311411` (visited on 05/11/2025).

[36] M. D. Bouguern, A. K. Madikere Raghunatha Reddy, X. Li, S. Deng, H. Laryea, and K. Zaghib, “Engineering dry electrode manufacturing for sustainable lithium-ion batteries”, *Batteries*, vol. 10, no. 1, 2024, ISSN: 2313-0105. DOI: `10.3390/batteries10010039`. [Online]. Available: `https://www.mdpi.com/2313-0105/10/1/39`.

[37] M. Haarmann, D. Grießl, and A. Kwade, “Continuous Processing of Cathode Slurry by Extrusion for Lithium-Ion Batteries”, *Energy Technology*, vol. 9, no. 10, p. 2 100 250, Oct. 2021, ISSN: 2194-4288, 2194-4296. DOI: `10.1002/ente.202100250`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/ente.202100250` (visited on 04/17/2025).

[38] Y. S. Zhang, A. N. Pallipurath Radhakrishnan, J. B. Robinson, *et al.*, “*In Situ* Ultrasound Acoustic Measurement of the Lithium-Ion Battery Electrode Drying Process”, *ACS Applied Materials &*

Interfaces, vol. 13, no. 30, pp. 36 605–36 620, Aug. 2021, ISSN: 1944-8244, 1944-8252. DOI: `10.1021/acsami.1c10472`. [Online]. Available: `https://pubs.acs.org/doi/10.1021/acsami.1c10472` (visited on 05/11/2025).

[39] X. Yu, M. Chen, M. Wang, *et al.*, "Effect of drying temperature on binder/current collector interfacial adhesion in electrode manufacturing of Li-ion batteries", *Manufacturing Letters*, 52nd SME North American Manufacturing Research Conference (NAMRC 52), vol. 41, pp. 304–309, Oct. 2024, ISSN: 2213-8463. DOI: `10.1016/j.mfglet.2024.09.036`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2213846324000981` (visited on 05/11/2025).

[40] Y. Chen, H. Tao, B. Li, B. Li, C. Lian, and H. Liu, "Modeling and Optimizing the Drying Process of Electrode Manufacturing for Lithium-Ion Batteries", *Energy Technology*, vol. 12, no. 11, p. 2 401 146, Nov. 2024, ISSN: 2194-4288, 2194-4296. DOI: `10.1002/ente.202401146`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/ente.202401146` (visited on 05/11/2025).

[41] Y. Purwamargapratala, M. Hardian, M. P. Pinem, E. Kartini, and A. Zulfia, "The Effect of Increasing the Thickness of NMC541 Cathode Calendaring on the Performance of Lithium-Ion Batteries", *Journal of Electronic Materials*, vol. 53, no. 1, pp. 121–128, Jan. 2024, ISSN: 1543-186X. DOI: `10.1007/s11664-023-10783-2`. [Online]. Available: `https://doi.org/10.1007/s11664-023-10783-2` (visited on 05/11/2025).

[42] M. Abdollahifar, H. Cavers, S. Scheffler, A. Diener, M. Lippke, and A. Kwade, "Insights into Influencing Electrode Calendering on the Battery Performance", *Advanced Energy Materials*, vol. 13, no. 40, p. 2 300 973, Oct. 2023, ISSN: 1614-6832, 1614-6840. DOI: `10.1002/aenm.202300973`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/aenm.202300973` (visited on 05/11/2025).

[43] H. Alolaywi, K. Uzun, and Y.-T. Cheng, "Low porosity NMC622 and NMC811 electrodes made by severe calendering", *Journal of Energy Storage*, vol. 105, p. 114 559, Jan. 2025, ISSN: 2352-152X. DOI: `10.1016/j.est.2024.114559`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2352152X24041458` (visited on 05/11/2025).

[44] H. H. Heimes, A. Kampker, C. Lienemann, *et al.*, *Lithium-ion battery cell production process*. Aachen: PEM der RWTH Aachen University, 2018, ISBN: 9783947920037.

[45] A. Wang, S. Kadam, H. Li, S. Shi, and Y. Qi, "Review on modeling of the anode solid electrolyte interphase (SEI) for lithium-ion batteries", *npj Computational Materials*, vol. 4, no. 1, pp. 1–26, Mar. 2018, ISSN: 2057-3960. DOI: `10.1038/s41524-018-0064-0`. [Online]. Available: `https://www.nature.com/articles/s41524-018-0064-0` (visited on 03/05/2025).

[46] J. Li, J. Fleetwood, W. B. Hawley, and W. Kays, "From Materials to Cell: State-of-the-Art and Prospective Technologies for Lithium-Ion Battery Electrode Processing", *Chemical Reviews*, vol. 122, no. 1, pp. 903–956, Jan. 2022, ISSN: 0009-2665, 1520-6890. DOI: `10.1021/acs.chemrev.1c00565`. [Online]. Available: `https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00565` (visited on 02/14/2025).

[47] W. B. Hawley and J. Li, "Beneficial rheological properties of lithium-ion battery cathode slurries from elevated mixing and coating temperatures", *Journal of Energy Storage*, vol. 26, p. 100 994, Dec. 2019, ISSN: 2352152X. DOI: `10.1016/j.est.2019.100994`. [Online]. Available: `https://linkinghub.elsevier.com/retrieve/pii/S2352152X19308734` (visited on 05/10/2025).

[48] Y. Kim, E. H. Jeong, B. S. Kim, and J. D. Park, "Comparative study on the rheological properties of natural and synthetic graphite-based anode slurries for lithium-ion batteries", *Korea-Australia Rheology Journal*, vol. 36, no. 1, pp. 25–32, Feb. 2024, ISSN: 2093-7660. DOI: `10.1007/s13367-023-00079-6`. [Online]. Available: `https://doi.org/10.1007/s13367-023-00079-6` (visited on 03/03/2025).

[49] S. Lim, S. Kim, K. H. Ahn, and S. J. Lee, "The effect of binders on the rheological properties and the microstructure formation of lithium-ion battery anode slurries", *Journal of Power Sources*, vol. 299, pp. 221–230, Dec. 2015, ISSN: 03787753. DOI: `10.1016/j.jpowsour.2015.09.009`.

[Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0378775315302718 (visited on 05/10/2025).

[50] S. H. Sung, S. Kim, J. H. Park, J. D. Park, and K. H. Ahn, "Role of PVDF in Rheology and Microstructure of NCM Cathode Slurries for Lithium-Ion Battery", *Materials*, vol. 13, no. 20, pp. 45–44, Oct. 2020, ISSN: 1996-1944. DOI: 10.3390/ma13204544. [Online]. Available: https://www.mdpi.com/1996-1944/13/20/4544 (visited on 02/17/2025).

[51] M. Ishii and H. Nakamura, "Influence of molecular weight and concentration of carboxymethyl cellulose on rheological properties of concentrated anode slurries for lithium-ion batteries", *JCIS Open*, vol. 6, p. 100 048, Jul. 2022, ISSN: 2666-934X. DOI: 10.1016/j.jciso.2022.100048. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666934X2200006X (visited on 03/04/2025).

[52] A. Cushing, T. Zheng, K. Higa, and G. Liu, "Viscosity Analysis of Battery Electrode Slurry", *Polymers*, vol. 13, no. 22, p. 4033, Nov. 2021, ISSN: 2073-4360. DOI: 10.3390/polym13224033. [Online]. Available: https://www.mdpi.com/2073-4360/13/22/4033 (visited on 03/22/2025).

[53] M. Ishii, S. Makino, and H. Nakamura, "The role of carboxymethyl cellulose on the rheology of anode slurries in lithium-ion batteries", *Current Opinion in Colloid & Interface Science*, vol. 74, p. 101 858, Dec. 2024, ISSN: 1359-0294. DOI: 10.1016/j.cocis.2024.101858. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1359029424000761 (visited on 03/04/2025).

[54] X. Lu, G. J. Lian, J. Parker, *et al.*, "Effect of carbon blacks on electrical conduction and conductive binder domain of next-generation lithium-ion batteries", *Journal of Power Sources*, vol. 592, p. 233 916, Feb. 2024, ISSN: 03787753. DOI: 10.1016/j.jpowsour.2023.233916. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0378775323012922 (visited on 03/23/2025).

[55] C. Reynolds, M. Faraji Niri, M. F. Hidalgo, *et al.*, "Impact of Formulation and Slurry Properties on Lithium-ion Electrode Manufacturing", *Batteries & Supercaps*, vol. 7, no. 2, pp. 1–19, Dec. 2023, ISSN: 2566-6223. DOI: 10.1002/batt.202300396. [Online]. Available: https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/batt.202300396 (visited on 02/17/2025).

[56] L. Ouyang, Z. Wu, J. Wang, *et al.*, "The effect of solid content on the rheological properties and microstructures of a Li-ion battery cathode slurry", *RSC Advances*, vol. 10, no. 33, pp. 19 360–19 370, 2020, ISSN: 2046-2069. DOI: 10.1039/D0RA02651D. [Online]. Available: https://xlink.rsc.org/?DOI=D0RA02651D (visited on 03/22/2025).

[57] D. Miranda, A. Gören, C. Costa, M. Silva, A. Almeida, and S. Lanceros-Méndez, "Theoretical simulation of the optimal relation between active material, binder and conductive additive for lithium-ion battery cathodes", *Energy*, vol. 172, pp. 68–78, Apr. 2019, ISSN: 03605442. DOI: https://doi.org/10.1016/j.energy.2019.01.122. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360544219301306 (visited on 03/22/2025).

[58] C. D. Reynolds, S. D. Hare, P. R. Slater, M. J. H. Simmons, and E. Kendrick, "Rheology and Structure of Lithium-Ion Battery Electrode Slurries", *Energy Technology*, vol. 10, no. 10, p. 2 200 545, Oct. 2022, ISSN: 2194-4288, 2194-4296. DOI: 10.1002/ente.202200545. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/ente.202200545 (visited on 03/23/2025).

[59] EBSCO, *Craap test — ebsco research starters*, https://www.ebsco.com/research-starters/social-sciences-and-humanities/craap-test, Accessed: 2025-05-11, n.d.

[60] *Web of Science*. [Online]. Available: https://www.webofscience.com/wos/woscc/summary/b292d749-31b8-4802-b141-2286fbb9943f-016071d9d4/relevance/1 (visited on 05/08/2025).

[61] M. Karlsson, *Former university relations manager for Northvolt*, Digital interview conducted on March 6, 2025.

[62] C. Rindi, *Researcher at Fraunhofer FFB*, Digital interview conducted on March 20, 2025.

[63] D. Collins, *Area sales manager at Bühler UK Limited and Bühler Nordics*, Digital interview conducted on April 14, 2025.

[64] *Writefull integration — overleaf*, `https://www.overleaf.com/learn/how-to/Writefull_integration`, Accessed: 2025-05-11, n.d.

[65] H. Dreger, H. Bockholt, W. Haselrieder, and A. Kwade, "Discontinuous and Continuous Processing of Low-Solvent Battery Slurries for Lithium Nickel Cobalt Manganese Oxide Electrodes", *Journal of Electronic Materials*, vol. 44, no. 11, pp. 4434–4443, Nov. 2015, ISSN: 1543-186X. DOI: `10.1007/s11664-015-3981-4`. [Online]. Available: `https://doi.org/10.1007/s11664-015-3981-4` (visited on 04/03/2025).

[66] C. Dahmen, F. Degen, M. C. Eckstein, *et al.*, *Mastering Ramp-up of Battery Production*, Oct. 2024. DOI: `10.24406/PUBLICA-3727`. [Online]. Available: `https://publica.fraunhofer.de/handle/publica/476968` (visited on 04/18/2025).

[67] P. S. Grant, D. Greenwood, K. Pardikar, *et al.*, "Roadmap on Li-ion battery manufacturing research", *Journal of Physics: Energy*, vol. 4, no. 4, pp. 1–8, Oct. 2022, ISSN: 2515-7655. DOI: `10.1088/2515-7655/ac8e30`. [Online]. Available: `https://iopscience.iop.org/article/10.1088/2515-7655/ac8e30` (visited on 04/19/2025).

[68] F. Jeschull, D. Brandell, M. Wohlfahrt-Mehrens, and M. Memm, "Water-Soluble Binders for Lithium-Ion Battery Graphite Electrodes: Slurry Rheology, Coating Adhesion, and Electrochemical Performance", *Energy Technology*, vol. 5, no. 11, pp. 2108–2118, Nov. 2017, ISSN: 2194-4288, 2194-4296. DOI: `10.1002/ente.201700200`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/ente.201700200` (visited on 04/03/2025).

[69] J. F. Meza Gonzalez, H. Nirschl, and F. Rhein, "Continuous Anode Slurry Production in Twin-Screw Extruders: Effects of the Process Setup on the Dispersion", *Batteries*, vol. 10, no. 5, p. 145, Apr. 2024, ISSN: 2313-0105. DOI: `10.3390/batteries10050145`. [Online]. Available: `https://www.mdpi.com/2313-0105/10/5/145` (visited on 04/17/2025).

[70] J. F. Meza Gonzalez and H. Nirschl, "Numerical investigation of the local shear rate in a twin-screw extruder for the continuous processing of li-ion battery electrode slurries", *Energy Technol [Internet]*, vol. 11, no. 6, e202201517, Jun. 2023, [cited 2025 Apr 17]. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/ente.202201517`.

[71] European Parliament, *EU ban on the sale of new petrol and diesel cars from 2035 explained*, Mar. 2022. [Online]. Available: `https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained` (visited on 05/11/2025).

[72] European Commission, *The European Green Deal*, Jul. 2021. [Online]. Available: `https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en` (visited on 05/11/2025).

[73] U.S. Congress, *H.r.5376 - inflation reduction act of 2022*, 117th U.S. Congress, Aug. 2022. [Online]. Available: `https://www.congress.gov/bill/117th-congress/house-bill/5376` (visited on 05/11/2025).

[74] Our World in Data, *Carbon intensity of electricity generation.* [Online]. Available: `https://ourworldindata.org/grapher/carbon-intensity-electricity` (visited on 05/12/2025).

[75] Carbone 4, *Increase the accuracy of carbon footprint for Li-ion battery.* [Online]. Available: `https://carbone4.com/fr/publication-liion-battery-carbon-footprint` (visited on 05/12/2025).

[76] European Chemicals Agency, *How to comply with reach restriction 71, guideline for users of nmp (1-methyl2-pyrrolidone)*, Accessed 13 May 2025, 2019. [Online]. Available: `https://echa.europa.eu/documents/10162/17233/entry_71_how_to_comply_en.pdf/c6e09198-c0b1-44e3-abae-6b3d0bc909a8` (visited on 05/13/2025).

[77] US EPA OCSPP, *Risk Management for n-Methylpyrrolidone (NMP)*, Overviews and Factsheets, Jan. 2016. [Online]. Available: `https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-n-methylpyrrolidone-nmp` (visited on 05/12/2025).

[78] E. Wiegmann, H. Cavers, A. Diener, and A. Kwade, "Semi-dry extrusion-based processing for graphite anodes: Morphological insights and electrochemical performance", *Energy Technology*,

vol. 11, no. 9, p. 2 300 341, Sep. 2023, ISSN: 2194-4288, 2194-4296. DOI: `10.1002/ente.202300341`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/ente.202300341` (visited on 04/03/2025).

[79] E. Wiegmann, A. Kwade, and W. Haselrieder, "Solvent reduced extrusion-based anode production process integrating granulate coating, drying, and calendering", *Energy Technology*, vol. 10, no. 6, Jun. 2022, ISSN: 2194-4288, 2194-4296. DOI: `10.1002/ente.202200020`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/ente.202200020` (visited on 04/08/2025).

[80] B. Ludwig, J. Liu, I.-M. Chen, *et al.*, "Understanding Interfacial-Energy-Driven Dry Powder Mixing for Solvent-Free Additive Manufacturing of Li-Ion Battery Electrodes", *Advanced Materials Interfaces*, vol. 4, no. 21, Nov. 2017, ISSN: 2196-7350, 2196-7350. DOI: `10.1002/admi.201700570`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/10.1002/admi.201700570` (visited on 02/17/2025).

[81] L. Fernandez-Diaz, J. Castillo, E. Sasieta-Barrutia, *et al.*, "Mixing methods for solid state electrodes: Techniques, fundamentals, recent advances, and perspectives", *Chemical Engineering Journal*, vol. 464, May 2023, ISSN: 1385-8947. DOI: `https://doi.org/10.1016/j.cej.2023.142469`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S1385894723012007`.

[82] B. Paredes-Goyes, F. M. Zanotto, V. Boudeville, S. Grugeon, L. Dupont, and A. A. Franco, "Mesoscopic model of extrusion during solvent-free lithium-ion battery electrode manufacturing**", *Batteries Supercaps*, vol. 7, no. 2, pp. 1–9, Feb. 2024, ISSN: 2566-6223. DOI: `10.1002/batt.202300441`. [Online]. Available: `https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/batt.202300441`.

[83] K. Zhang, D. Li, X. Wang, *et al.*, "Dry electrode processing technology and binders", *Materials*, vol. 17, no. 10, 2024, ISSN: 1996-1944. DOI: `10.3390/ma17102349`. [Online]. Available: `https://www.mdpi.com/1996-1944/17/10/2349`.

[84] V. Boudeville, S. Grugeon, A. Maurel, *et al.*, "Solvent-free extrusion of a LiFePO4-based monofilament for three-dimensional printing of a lithium-ion battery positive electrode", *Journal of Power Sources*, vol. 593, p. 233 973, Feb. 2024, ISSN: 0378-7753. DOI: `10.1016/j.jpowsour.2023.233973`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0378775323013496`.

[85] Natural Resources Canada, *Cobalt facts*, Mar. 2023. [Online]. Available: `https://natural-resources.canada.ca/minerals-mining/mining-data-statistics-analysis/minerals-metals-facts/cobalt-facts` (visited on 05/12/2025).

[86] European Parliament and Council of the European Union, *Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC*, Official Journal of the European Union, L 191, 28.7.2023, p. 1–116, Jul. 2023. [Online]. Available: `https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng` (visited on 05/11/2025).

[87] L. Mancini, N. A. Eslava, M. Traverso, and F. Mathieux, "Assessing impacts of responsible sourcing initiatives for cobalt: Insights from a case study", *Resources Policy*, vol. 71, Jun. 2021, ISSN: 0301-4207. DOI: `10.1016/j.resourpol.2021.102015`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0301420721000325` (visited on 02/14/2025).

A Appendix

A.1 Interview guide 1

During the interview with Martin Karlsson, former University Relations manager in Stockholm, Sweden, the following questions were used as a guide. The original interview was conducted in Swedish, and the questions are presented in both Swedish and their English translations.

1. **Swedish:** Kan du berätta lite om din nuvarande roll och vilken typ av projekt du arbetar med?
   English: Could you tell us a bit about your current role and the types of projects you are working on?

2. **Swedish:** När företag överväger nya tillverkningstekniker, som till exempel kontinuerliga mixers, hur brukar den utvärderingsprocessen se ut enligt din erfarenhet?
   English: When companies consider new manufacturing technologies, such as continuous mixers, what does the evaluation process typically look like based on your experience?

3. **Swedish:** Vad är din erfarenhet av hur företag generellt går till väga när de utvärderar ny tillverkningsteknik?
   English: What is your experience of how companies generally approach the evaluation of new manufacturing technologies?

4. **Swedish:** Känner du till om kontinuerliga processer har övervägts i några projekt du har varit involverad i?
   English: Are you aware of any projects you have been involved in where continuous processes have been considered?

A.2 Interview guide 2

During the interview with Carola Rindi, Research Associate at Fraunhofer Research Institution for Battery Cell Production (FFB), in Münster, Germany, the following questions were used as a guide.

1. Pros and cons with batch and continuous mixing.
2. Are the companies considering continuous mixing?
3. Why do you think cont. mixers is not standard?
4. How are the properties of the slurry affected with the cont. mixing compared to batch mixing?
5. How are the properties of the slurry affected with the cont. mixing compared to batch mixing?
6. How well the cont. mixing can adapt to different compositions?
7. Is continuous mixing the future?

A.3 Interview guide 3

During the interview with Dave Collins, area sales manager at Bühler Technologies, the following questions were used as a guide.

1. From your perspective, how would you describe the current market demand for continuous slurry mixing solutions in the battery manufacturing industry?
2. Are the manufacturers aware of the continuous mixing alternative?
3. In your experience, what are the factors like cost, energy use, or scalability which influence customer decisions when choosing mixing technique?
4. How do the investment cost compare between a batch and a continuous mixing process? If more expensive; how do you motivate the relatively expensive investment cost, compared to batch?
5. When operating, how much more efficient is the continuous mixing compared to batch mixing? Cost saving through labour cost, waste, lower energy usage etcetera.
6. What types of customers do you typically work with when it comes to continuous slurry mixing — are they mostly R&D labs, pilot plants, or full-scale manufacturers? Location?
7. Are your customers typically new battery manufacturers designing new production lines, or more established producers transitioning from batch mixing to continuous systems? And in the case of existing facilities — how compatible is Bühler's continuous mixing technology with current production lines?
8. Are Bühler's continuous mixing systems already being delivered to production-scale facilities? If so, how long does a typical project take from order to commissioning?
9. Looking at solvent-reduced slurries and dry battery electrode manufacturing, can this be done with the same twin-extruders as normal slurries or do you need to invest in new equipment to manufacture this?
10. Is continuous mixing the future? Is development of continuous mixing the main focus in the industry? Other solutions in the future?