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Production technologies and systems for electric mobility

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A B S T R A C T

Achieving CO_2-neutral transportation requires large-scale electric vehicle production, posing significant manufacturing challenges. Electric vehicles consist of components with multi-physical functionalities and intricate interdependencies that exceed the capabilities of current production systems. This paper examines key drivetrain components, including power supply systems, batteries, power electronics, and traction motors. It reviews state-of-the-art manufacturing and associated challenges. Analytical and numerical modeling approaches as well as product-specific trends are highlighted. Furthermore, the paper puts emphasis on life cycle assessment (LCA) and life cycle engineering (LCE), as electric drivetrains pose distinct challenges compared to conventional drivetrains. Lastly, future research demands for electric mobility production technology and component-specific research fields are outlined.

1. Introduction and motivation

Mobility is a basic human need [268]. Throughout history, humans have continually strived to cover greater distances over extended periods and to transport heavy cargo, all while minimizing physical exertion. To fulfill this ambition, people have consistently made full use of the prevailing technological advancements of their respective eras. One milestone was the emergence of the automobile in the late 19th century, which sparked what is now known as the second transportation revolution. This revolution ushered in an era characterized by enhanced individual mobility. Today, in most industrialized countries, almost 80 % of domestic journeys in terms of distance covered are made by car (private car, taxi or carsharing) [24].

As such, an electric vehicle (EV) is not a recent invention. The beginnings of electrified passenger transportation date back to the mid-19th century. The first test run of an EV took place in 1839, and the first test run of an electric locomotive in 1851. The initial boom of e-mobility until around 1900 was slowed down by high dependence on national infrastructures. As of today, the availability of a robust public charging infrastructure remains a challenge in several countries, and fast charging infrastructure in particular is insufficient. Even on dedicated transport routes, such as railways, e-mobility lags behind internal combustion engines on a global scale (only about 30 % of the world's railway tracks are electrified) [207].

Thus, for the past hundred years, the internal combustion engine (ICE) has been the dominant power source in the transportation sector and specifically for passenger vehicles. Liquid fossil fuels are by far the most dominant source of energy. This is due to their high energy density and their ability to be stored in simple on-board tank systems, allowing vehicles to travel long distances without being connected to the infrastructure. As a result, only a few infrastructure nodes are required to enable decentralized refueling. Applying this requirement profile, two possible approaches can be identified: (1) the use of large energy storage systems in the vehicle in combination with existing infrastructure density or (2) a much denser network of charging nodes in combination with small energy storage systems.

However, apart from their high energy density, burning fossil fuels renders internal combustion engine vehicles (ICEV) a major source of global greenhouse gas (GHG) emissions. Globally, the transportation sector ranks as the fourth-largest source of GHG emissions. In 2019, the transportation sector was responsible for approximately 8.9 gigatons (Gt) of CO_2 equivalents (CO_2-eq) representing the global warming potential (GWP). With 6.1 Gt CO_2-eq, passenger and freight road transport are responsible for more than two-thirds of the transportation sector's emissions. The road transport emissions have increased by a factor of 1.7 compared to 1990 [120].

Efforts to mitigate climate change and drastically reduce GHG emissions have placed the transportation sector, and the ICE in particular, at the center of public debate. At least since the Paris Climate Agreement of 2015, there has been a commitment to reduce GHG emissions significantly to keep the increase in global average temperature well below 2 degrees Celsius above pre-industrial level. In addition, there are other regulatory frameworks and target agreements such as "Fit for 55" in the European Union (EU), where the EU declares to reduce net GHG emissions by 55 % by 2030 [61], the Chinese five-year plan [242] and the long-term strategy of the United States [269]. As an example, in an effort to reduce GHG emissions in

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the transportation sector, that are responsible for one fifth of GHG emissions in the EU, the European Council bans the sale of new petrol and diesel cars by 2035 [62]. This has led to a shift in the mobility sector towards e-mobility.

EVs exhibit significantly lower GHG emissions compared to ICEVs though it is their emission-free operation that warrants particular attention. This absence of exhaust emissions eliminates air pollutants such as nitrogen oxides and other harmful substances, providing substantial relief to densely populated urban areas, which are disproportionately affected by high traffic density. Furthermore, EVs demonstrate reduced operating and maintenance costs due to their simpler mechanical design. Additionally, EVs offer superior driving comfort relative to ICEVs, attributable to their lower noise emissions and enhanced acceleration capabilities.

One of the main reasons why EVs play an important role not only towards mitigating climate change, but also supersede ICEVs, lies in the increased efficiency of the vehicle concept. As illustrated in Fig. 1, the efficiencies of battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and ICEVs (powered by E-Fuel, a synthetic fuel made with renewable electricity) differ substantially. Beginning with the availability of 100 % renewable energy, various energy losses occur throughout the energy supply chain until the energy is delivered to the vehicle's tank or battery (well-to-tank). The losses within the vehicle and its drivetrain further reduce overall efficiency (tank-to-wheel). For BEVs, the overall efficiency is 77 %. Of the remaining 94 % of energy supplied to the vehicle, only 17 % is lost in the electric drivetrain. The losses are 35 % for the FCEV and 39 % for the ICEV. The well-to-tank as well as the tank-to-wheel losses are much higher and clearly demonstrate the efficiency advantages of BEVs over other drive concepts compared to ICEVs (16 % overall efficiency) and FCEVs (33 % overall efficiency) [261].

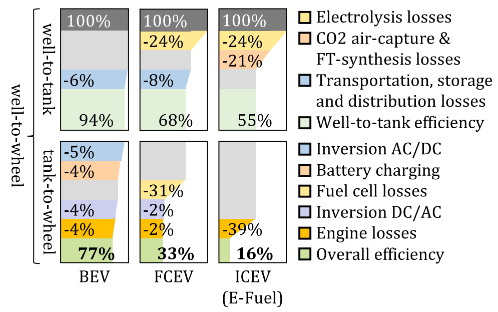

Fig. 1. Efficiency of BEVs, FCEVs and ICEVs according to [261].

However, when comparing lower GHG emissions and high efficiency of the EV to that of the ICEV, there are additional cascading industrial demands which need to be addressed simultaneously during the development of both new product and production technology. An example of this is meeting the energy density (Wh/kg) requirements (high for ICEVs) while taking into account the market and product performance needs, which can be expressed as: (1) cost and weight (low cost and lightweight for micro-mobility/automotive applications; with a medium energy density level of 300Wh/kg); and, (2) weight and power density (lightweight and high energy density level >400Wh/kg for electric Vertical Take-Off and Landing aircrafts (eVTOLs) and all electric aero applications).

Given the transformative nature of e-mobility and the importance of mitigating climate change, the aim of this paper is to provide an overview of the relevant research on the manufacturing of drivetrain of EVs, highlighting the major challenges and driving future research demands. Therefore, Section 2 introduces the requirements for the manufacturing processes and production systems to produce the main functional components of an EV drivetrain (Fig. 2).

In the following sections, each of these drivetrain components are examined in detail. This includes the power supply in Section 3, covering power transfer via the infrastructure (inductive and conductive) as well as on-board power generation by fuel cells. The manufacturing of energy storages in the form of batteries is discussed

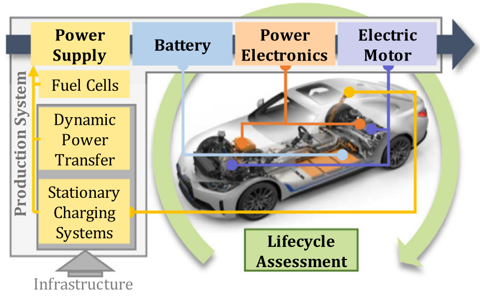

Fig. 2. Main functional components of an EV drivetrain.

in Section 4. Section 5 focuses on the manufacturing of power electronics. Finally, the manufacturing of electric motors is addressed in Section 6. In each of these sections the component itself, the manufacturing process chains and their challenges are described as well as the essential state of the art core manufacturing processes are presented. In addition, analytical, numerical and data-based modeling approaches and implications of product-specific trends on production are identified. Section 7 continues by examining how a comprehensive life cycle assessment can be integrated into the product and process development in terms of a life cycle engineering of EVs. The concluding Section 8 provides a synthesis built on the research needs outlined in the preceding sections and formulates future research directions.

2. Requirements for manufacturing processes and production systems for electric mobility

Suitable and efficient production technologies and systems are required for the large-scale production of EVs. Partly, these differ fundamentally from the existing ones. For this reason, the challenges and requirements for the manufacturing of EV drivetrain components must be addressed first. This section therefore lists the specific requirements to manufacture these components.

At its core, the requirements are characterized by complex and multi-physical dependencies (mechanical, electrical, electrochemical, ...) that are not yet fully understood. While ICEV manufacturing primarily focuses on the mechanical properties of components, EV components also have chemical, electrical, electromagnetic, and thermal properties that need to be managed during manufacturing. Additionally, these dependencies are evolving dynamically as new product technologies are rapidly introduced to the market, which leads to a strong need for co-evolution of product and processes during their lifecycle [168,260].

In contrast to ICEVs, the dependence of EVs on infrastructure is classified as high, due to the not as yet fully comprehensive power supply because there is an important trade-off between product technology needs as measured by energy density and storage capacity versus density of surrounding infrastructure nodes to enable decentralized refueling/recharging. For this reason, immediate efforts to speed up the systematic expansion of infrastructure are necessary. The challenge however is the expansion of grid capacities on the one hand and the decentralized provision of electricity in a widespread charging network on the other. With a view to the increasing demand for electrical energy, additional power plants based on renewable sources should also be built in order to meet this demand in a CO_2-neutral manner. The existing and exacerbating infrastructural gap can only be met by the industrialization of its manufacturing. Therefore, various established manufacturing processes must be adapted to the requirements of these infrastructure.

The manufacturing of products with multi-physical functionalities has reached a new level of complexity and variety of process chains and their demands on the production system. In contrast to the previously discrete production at system level, the production system for e-mobility must also handle continuous processes. The manufacturing of batteries with the transition from a continuous mixing process via subsequent handling of sheet material to a discrete battery cell can be classified as hybrid processing that demonstrates this shift. Hence, the separation into single manufacturing processes and the simultaneous scaling of the production system is very challenging.

Furthermore, when these requirements permeate into the development of production technology, and with current needs for rapid ramp-up and high-rate production, there is a further strong need for analytical, numerical and data-driven modeling approaches like deep learning-enhanced simulation approaches enabling scaling up production from "concept readiness" to "production readiness" based on key enabling technologies such as "life cycle analytics" that contribute towards a new paradigm of creating closed-loop production systems and factories [68]. This can ensure production of nearly zero-defects products (e.g., needed to satisfy safety of battery systems), to be developed and deployed in production faster, better and cheaper by accomplishing a high rate of "right-first-time" (RFT). The principles guiding closed-loop e-mobility production systems and factories result from realities on the ground: Products, manufacturing processes and interlinked services are challenged by external drivers such as new regulations, new materials, technologies, services and communications and the pressure on cost and sustainability, all of which requires coordinated co-evolution of products, production systems and services [30].

Considering different market penetration scenarios for EVs, production capacity and scalability is of high relevance, i.e. scaling up production volumes will result in higher degree of automation [225]. This is supported by the use of standardized interfaces in the machinery. If production systems are modular and flexible, it is easier to respond to different product variants and quantities, which are becoming increasingly common due to variable product life cycles. In terms of sustainability, the reuse of structure components, including product optimization through software updates, enables new business models for OEMs. Thus, an orchestrated ramp-up is becoming increasingly important. This is also due to the fact that there are diverse requirements for the production system. The variety of characteristics of e-mobility components (e.g., electric motor) and their parts (e.g., bearings) is as great as the choice of a suitable production method: some manufacturing processes are suitable for large-scale production, others are flexible but more expensive. In addition, some types of electric motors require special manufacturing or assembly processes that are not necessary when manufacturing other types of electric motors. Due to the significant uncertainty associated with product development, investments in highly productive but inflexible production systems are seen as considerable [224].

The high degree of uncertainty necessitates optimized production planning. Existing integrated approaches for production planning can be organized along the architecture of the production system, and the key aspects are specific to unique characteristics. To improve production systems for e-mobility, engineers and designers across various disciplines need integrated methods and tools. These tools must be designed to support the analysis of the effects of planning and design decisions on the production systems and products, providing insights into their static and dynamic characteristics as well as the resulting properties. Approaches such as Product-Production-CoDesign and co-evolution can support engineers and designers [3,184,260].

In addition, the use of rare earth materials, e.g., in magnets for electric motors, is common in automotive applications in order to achieve maximum performance. The demand for rare earth materials is increasing due to expected EV market developments. While the extraction of these materials can lead to an increased dependence on certain suppliers from certain countries, energy-intensive mining can additionally create a high carbon footprint of the products, which has to be considered in life cycle assessment. For this reason, it is necessary to reduce GHG emissions in all manufacturing processes, as a large number of materials are used and the processes are very energy-intensive. Furthermore, it is necessary to prepare the manufacturing systems for circular economy. To enable a circular economy, the remanufacturing of e-mobility components must already be taken into account in the planning phase of production processes and systems. Disassembly and recycling approaches are highly relevant for all EV components. A quantification methodology is mandatory to reach sustainability (see Section 7).

Due to these challenges in the production of e-mobility components and the associated challenge of reducing costs, research is required particularly at component level. The latest findings and advances must be brought to market as quickly as possible and immediately implemented in the industry. The next sections therefore explain particular challenges at component level.

3. Manufacturing of power supply systems

As discussed in Section 2, the provision of electricity for EVs via the current infrastructure is a major challenge preventing the wider adoption of EVs. Due to this dependency on the infrastructure, the industrialization of manufacturing is of crucial importance. Therefore, several existing manufacturing processes must be adapted to the requirements of the infrastructure and the associated multi-physical functionalities must be taken into account. This section first discusses systems for static and dynamic charging before focusing on the manufacture of fuel cells.

3.1. Manufacturing of static and dynamic charging systems

Charging systems for e-mobility comprise key decision-making features that have a major influence on the design of the system and thus also on its manufacturing. Before the challenges and developments of charging systems are discussed in detail, it is important to first distinguish their product-specific features. Therefore, the next paragraphs will first describe these features before addressing the manufacturing of charging systems starting from Section 3.1.1.

A distinction can be made between the type of connection and the type of vehicle motion. The connection can be established by conductive or inductive methods. Conductive charging requires a physical connection via an electrical contact of conductors, while inductive charging enables wireless charging using electromagnetic induction. Vehicle motion includes stationary, semi-dynamic and dynamic charging. Stationary charging occurs at fixed locations, such as fast charging stations or at home, work or shopping locations. Semi-dynamic charging takes place during short stops of the vehicle, such as at taxi ranks, traffic lights, or bus stops. Dynamic charging involves charging while the vehicle is in motion, typically using dedicated lanes on highways [131,213].

With reference to conductive charging systems, the focus in the following sections is on stationary systems. These systems establish a plug-based conductive connection between the EV and the charging infrastructure. A distinction is made between public and private use as well as the charging speeds. Public charging systems are freely accessible and comply with local standards for weights and dimensions, with additional features such as vandalism protection. In contrast, private charging systems, such as wall boxes for home charging, operate within a protected environment. Additionally, charging systems can be categorized as slow charging, with power levels up to 22 kW and mainly utilizing AC charging (see Fig. 3.A), or fast charging, exceeding 22 kW and predominantly employing DC charging. Fast charging systems require additional components like an AC/DC converter (rectifier) and an active cooling unit, with the

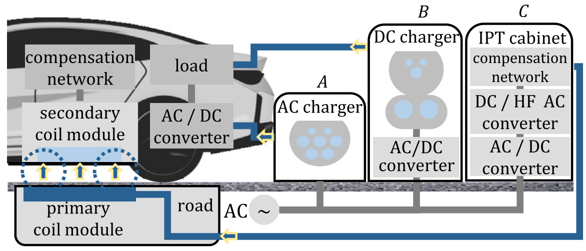

Fig. 3. Components of conductive AC and DC charging systems and inductive power transfer systems. Image source: BMW AG.

charging process managed by the charging station itself (see Fig. 3.B) [218].

The global expansion of EV charging infrastructure has witnessed a remarkable growth in recent years. By the end of 2022, there were approximately 2.7 million public charging points worldwide, marking a significant milestone. In 2022 alone, over 900,000 new charging installations were installed, representing an impressive 55 % increase compared to the previous year.

This surge in installations comprised 600,000 new public slow charging points and 330,000 new public fast charging points. These figures underline the substantial efforts and investments being made to support the growing demand for EV charging on a global scale [119].

Inductive power transfer (IPT) systems enable the efficient contactless transfer of high power [196]. A coupled coil system consisting of a primary and a secondary coil modules bridges an intermediate air gap by building up an alternating magnetic field (see Fig. 3.C) [137,178]. Besides, a wireless bidirectional communication between infrastructure and vehicle takes place [196]. The efficiency depends on the transmission frequency, area and relative positioning of the coils to each other [212,218]. In addition, IPT encourages frequent short charging at specific points (e.g., at bus stops) with automated grid connection without manual user intervention [196]. IPT systems also allow for dynamic charging while driving by sequential coil segments and adaptation of the alternating magnetic field to the vehicle speed [44,179].

3.1.1. Process chain for manufacturing of charging systems

The production of stationary charging systems involves several stages, ensuring the efficient and reliable operation of the charging infrastructure. AC and DC systems have the preparation of the housing as a starting point in common, similar to control cabinet construction.

For AC systems, the mounting plate assembly begins with the installation of a mounting rail or top hat rail. Standardized components such as the residual current device (RCD), residual current monitor 6 mA (RCM), power contactor, and connector blocks are mechanically placed on the mounting plate, following established practices in control cabinet construction. A large part of the wiring can take place on the mounting plate. In the case of DC systems, the rectifier module assembly follows a modular design including the integration of a cooling unit.

In the final assembly stage, the pre-assembled and wired mounting plate for AC systems is attached, while the rectifier modules for DC systems are positioned. The modules are securely fastened and a comprehensive electrical test is carried out to ensure that they function properly. Parts of IPT systems are the oscillating circuit modules, which are required on the infrastructure and vehicle side. The manufacturing processes on primary coil modules and secondary coil module are largely the same and are illustrated in Fig. 4, using the primary coil side as an example. For the large-scale primary flat coils, flat coils made of high-frequency stranded wire are first laid, then contacted with an electronic unit, and this unit is encapsulated by a potting process. A ferrite mirror can be integrated behind the flat coil to increase the coupling and thus the transmission efficiency between the coils.

3.1.2. Challenges on manufacturing processes and systems

Scalability is a major challenge when planning the charging system production, as the demand is unpredictable and yet increasing [109]. Another hurdle is to consider the wide range of conductive, stationary charging systems, including mounting types, connectivity packages, communication options, cable or socket version, power classes, fleet or master units, and customized aesthetics. Flexible production systems, careful planning, and supplier collaboration are crucial for overcoming these challenges.

Therefore, pilot projects and initial major technology implementations are required to demonstrate dynamic loading technology. The high volatility of demand requires flexible assembly and handling technologies as well as scalable processes with a high degree of automation for high volumes, especially for large-scale dynamic charging applications such as highway lanes [22]. At the same time, product-side performance increases result in more complex coil topologies (e.g., three-dimensional structure, transitions, multi-coil systems), which in combination with increasing functional integration (e.g., power electronics, communication modules) complicate manufacturing [12,22]. The production of large-area modules additionally affects the handling and manufacturing of components, especially for primary coils.

3.1.3. Core manufacturing processes

The following section describes the production of the charging infrastructure in detail. As the process chains for stationary charging systems (SCS) and dynamic charging systems (DCS) differ greatly, they are examined in the following sections based on the corresponding assembly groups from Fig. 3. The core manufacturing processes mentioned in this section are marked in red in Fig. 4.

3.1.3.1. Component placement. The robot-assisted assembly of standardized components on a mounting rail benefits from automation and the automatic generation of robot programs using ECAD data in multi-variant production. The challenge with automation lies in quality control, which is based on monitoring the locking mechanism, including secondary locking with force/torque detection. Due to the complexity of the joining movement, it is not trivial to reconstruct the force curve and ensure the correct fit of the component [257].

3.1.3.2. Electric wiring. Driven by automation approaches in the wire harness sector [262], automated wiring also has high potential for further industrialization of charging system manufacturing [162].

Due to the changing geometry, perception is one of the key factors in handling these components and creating opportunities for automated processing. This results in a large demand for sensor technology, which entails high costs for process automation. To achieve automated plugging, the perception of cable tips is crucial and subject of several scientific publications [84,100,101]. However, low-cost perception approaches often fail to deliver accurate results [79].

In the field of electric wiring, screw-type terminals are commonly used but they are difficult to wire automatically. The push-in terminal offers potential for automation due to its unilateral accessibility, linear joining path, and joining forces dependent on a spring

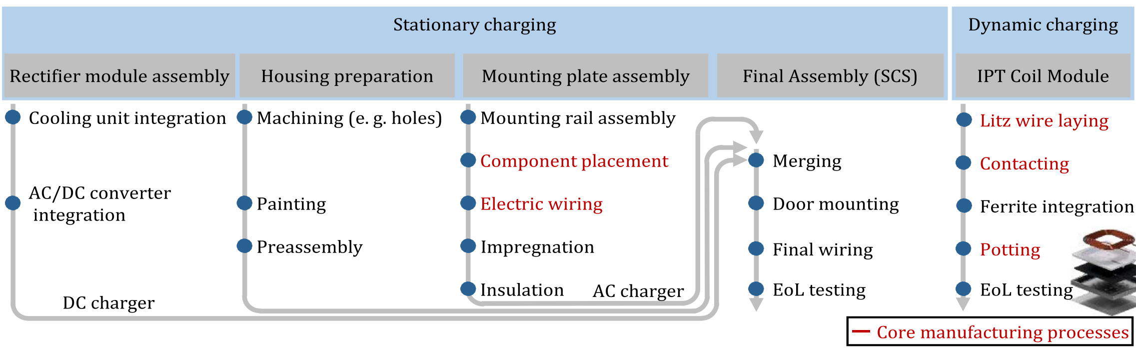

Fig. 4. Process chain for manufacturing of static (left) and dynamic charging systems (right) according to the industrial state-of-the-art.

mechanism. However, the latest development in the industry, the snap-in terminal, surpasses the push-in terminal by requiring fewer joining forces [75].

3.1.3.3. Litz wire laying for IPT systems. Flat coils are manufactured by laying high-frequency stranded wire in a specific topology. Besides potting, this process step has the highest prioritization in terms of process time and cost [214,280]. High variation of geometry and coil dimensions requires the application of flexible processes [213,214]. In this context, the adaptation of standardized winding technologies, such as linear or flyer winding, is not feasible for complex coil topologies, whereby CNC gantry systems or robot-based laying devices are applied [213,282]. Principally, different basic kinematic concepts are used, such as a moving coil carrier, moving strand feed or a combination of these [213,280].

The speed and flexibility of the process is largely determined by the fixing principle used, with mechanical or adhesive methods being employed [214,280]. Another challenge is the application of a defined strand tensile force over the entire laying process to avoid damage to the strand and to maintain the tight position tolerances [213,280].

3.1.3.4. Contacting of litz wire for IPT systems. Secondly, the strand ends are contacted with the power electronics to create a reliable electrical and mechanical connection for operating frequencies of up to 85 kH [280]. During contacting, thermic or ultrasonic removal of the primary insulation of the individual conductors is required, for example by soldering, hot crimping or ultrasonic welding [213]. Here, the automation capability and the joining of large strand diameters pose challenges to the process and are therefore the subject of research [213,229,280]. Hot crimping and ultrasonic welding furthermore require iterative test processes for different material combinations, using aluminum or copper-clad-aluminum as conductor material in addition to copper [214,280].

3.1.3.5. Potting of electrical components for IPT systems. The potting process is of central importance in the production of IPT systems, as a complete enclosure of the internal electronic components must be ensured in order to guarantee long-term protection against environmental influences. In addition, the potting resin ensures the mechanical cohesion of the components and absorbs mechanical (pressure) loads, for example from vehicles passing over them [213,280]. This step is particularly time-critical due to long curing times and thus represents a bottleneck in the design of the manufacturing process [213].

3.1.4. Analytical, numerical and data-based modeling approaches

Based on digital twins from the electronic and mechanical design of control cabinets such as charging stations, manufacturing operations can be planned and executed automatically from electrical computer-aided design [156]. To enable automation solutions for handling cables, there are a number of model-based representations of linear deformable behavior. While mass-spring and multi body models are computationally efficient but offer limited accuracy, elastic rod and dynamic spline models are more accurate but more computationally intensive. Finite element models provide the most accurate results, but are the most computationally intensive and not real-time capable [157]. The choice of an appropriate simulation model is crucial for simulations ranging from robotic manipulation to automated path planning [232].

Numerous efforts address the simulation-based optimization of the IPT system design. FE simulation approaches are also used to quantify the manufacturing influences on the product quality of IPT systems. In addition, numerical approaches are used to directly support manufacturing process design, e.g., for the winding process of HF-litz wire [282].

3.1.5. Implications of product-specific trends on production

The further development of static charging systems is primarily focused on increasing power transmission. The SAE J2954 standard, which defines wireless power transfer (WPT) for electric vehicles, aims to support input voltages of up to 60 kVA with WPT5, the fifth generation of wireless charging technology, in the future [218]. The impact on the core production processes should, however, be manageable. For dynamic charging, the high number of units required presents a significant manufacturing challenge, emphasizing the need to reduce costs through highly automated manufacturing and assembly processes. To address this, the establishment of large-scale production lines and processes for the modules is essential. Moreover, the largely undefined installation process of the modules into the infrastructure further influences the production methods, adding complexity to the overall manufacturing approach [178]. In addition, the recycling of IPT modules in the context of road rehabilitation depends heavily on the combination of materials used. Design for recycling approaches can therefore still influence the manufacturing processes. Fig. 5 shows the two main modules of an inductive charging system and a winding machine concept which is essential for large-scale production.

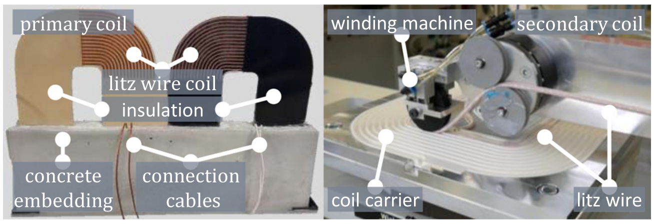

Fig. 5. Left: Main modules of an inductive charging system with a primary coil embedded in the infrastructure. Right: Winding machine concept for automated litz wire laying of the secondary (vehicle) coil. Image source: Institute FAPS.

3.2. Manufacturing of fuel cells

In comparison to charging systems, the fuel cell is a power supply system which is directly integrated into the drivetrain system with the hydrogen tank. While the first prototype of a fuel cell electric vehicle (FCEV) dates back to 1994, when Daimler introduced the NECAR, Toyota and Hyundai only commenced serial production in the last decade. However, the substantial production costs have continued to hinder widespread market introduction of these vehicles until today. Despite these challenges, fuel cells offer a promising solution for powering vehicles by converting chemical energy into electricity. Depending on the operating temperature and the type of electrolyte, fuel cells can be classified into different types. However, only the polymer electrolyte membrane fuel cell (PEMFC) is relevant for mobile applications due to its high power density and dynamic performance.

The heart of a fuel cell system is the stack. A fuel cell stack typically consists of several hundreds of unit cells, each comprising two core components: the membrane electrode assembly (MEA) and the bipolar plate (BPP). The functional core of a fuel cell is the polymer electrolyte membrane (PEM), which allows proton conduction but prevents gas permeation and electron transport between the anode and cathode side. The membrane is usually coated on both sides with a catalyst-ionomer-suspension to form the catalyst coated membrane (CCM). To prevent gas leakage, two so-called subgaskets with cutouts for the active area are laminated on both sides of the CCM [26]. With the trend towards mass production and automatic handling, different sealing designs regarding the material, location and application methods of sealings have been developed, such as seal-on-MEA or seal-on-gas diffusion layer (GDL) [298]. The subgasket-concept also known as 7-layer-MEA is often used in industrial applications due to short cycle times in manufacturing without a time-consuming injection-moulding process, and an efficient processability in a continuous roll-to-roll (R2R) process [121].

In addition to the sealing function, the subgasket strengthens the mechanical stability of the fragile CCM and facilitates the handling process. On top of the CCM, the gas diffusion layers are applied on both the cathode and anode side to ensure homogenous gas transport by a porous structure. Depending on the manufacturing technology, the GDL is typically a paper, felt or cloth made of carbon fibers. The side of GDL towards CCM can also be coated with a microporous layer (MPL) to ensure better gas transport [103]. In order to transfer the generated electrons and dissipate heat, a good electrical and thermal conductivity are also essential properties of the GDL [42,55,300]. The other core component in a cell unit is the BPP, which consists of two monopolar plates, one on the anode side and the other on the cathode side [43]. The monopolar plates of two adjacent cells are joined together to guarantee the gas tightness between hydrogen and oxygen as well as to build channels for the coolants, which is why it is generally referred to as a bipolar plate. The BPP is not directly of electrochemical interest, but carries lots of critical features which influence the cell performance and pose challenges for mass production. Approximately 300–600 cells need to be sequentially stacked and interconnected to achieve a high power density.

3.2.1. Process chain for fuel cell manufacturing

The manufacturing process for PEM fuel cells can be divided into BPP manufacturing, MEA assembly and final stack assembly (see Fig. 6). The core manufacturing processes mentioned in this section are marked in red in Fig. 6. The first step in BPP manufacturing is the forming of the metal sheet or foil with the designed contour of the flow fields and distributor structure. Besides, the area for intake and exhaust manifolds must be removed. To implement this process in one production line, progressive die stamping is widely used [253]. Alternative technologies are hydroforming [160], rubber pad forming [56] or high-velocity impact forming, where the cutting process needs to be carried out separately. After the monopolar plates are formed, two corresponding plates are joined mostly by laser welding. Adhesive bonding is also a possible joining method, especially for the graphite composite BPP, which requires an electrically conductive adhesive. Afterwards, a corrosion-resistant material is coated on the BPP to increase its stability in the acidic and warm environment during operation. An exchanged sequence of the stamping and coating process is also possible as a compromise between cost and quality. Subsequently, the sealing material is applied to the BPP or screen-printed onto it. After passing the leakage test, the BPP is delivered to the stacking machine [204].

The manufacturing of CCMs begins with the ink mixing process. The catalyst particles, normally platinum or platinum alloy, are carried by the carbon support and mixed with the same ionomer as the PEM to form the catalyst ink. To disperse the catalyst ink on the membrane, the so-called decal transfer process is widely used. In this process, the catalyst layer is first coated and dried on a transfer film (decal film) and then transferred via a hot pressing process onto the membrane to form the CCM [233,255]. As an alternative, the catalyst layer can be directly coated on the membrane, which is a challenging process due to the swelling effect of the membrane during hydration [198]. The base material of the GDL is carbon fiber. The manufacturing processes used in industrial production were adopted from the textile and paper industry [294]. The intermediate product gas diffusion substrate is coated with MPL and impregnated in polytetrafluoroethylene (PTFE) to optimize the gas diffusion and water management properties and build a protective barrier for CCM [103]. The subgasket made of polyethylene naphthalate (PEN), coated with a one-sided adhesive layer and perforated with cutouts for the active area and manifolds is laminated with the edge of the CCM and itself to form a flat sealing against gas leakage [35]. Furthermore, the GDLs can also be cut into single sheets and joined on the subgasketed CCM to finish the 7-layer MEA [20,121,146].

Afterwards, hundreds of unit cells are stacked to form a fuel cell stack with sufficient power density for mobile applications. The stacking process is started from the end plate. Commonly used handling systems for the limp and fragile BPP and MEA are vacuum suction grippers to prevent deformations and scratches by conventional grippers [221]. Articulated robots, gantry robots or delta pickers are used as kinematics in the pick-and-place process with regard to flexibility and cycle time requirements [222]. After compression with a design-specific assembly force, the stack is fixed with metallic compression bands or threaded rods. The assembly process ends with the mounting of the media supply modules, where multiple functions, such as media interfaces and water separators, are integrated [19,67,125].

3.2.2. Challenges on manufacturing processes and systems

Due to the miscellaneous material properties and complex functionality of the components, material-process-performance correlations need to be understood to improve the manufacturing processes. The process chain starts with the PEM manufacturing. The PEM is made of ionomer containing a hydrophilic side chain, which causes water absorption and desorption. This hygroscopic property leads to dimensional changes of the membrane in all directions [82,83]. Tang et al. [254] report an elongation of about 6 % for Nafion 112, one of Chemours' commonly used membranes, with an increase in relative humidity of only 10 % (see Fig. 7).

Furthermore, the thin membrane (down to 8 µm) is sensitive to extraneous particles which might puncture the membrane and form pinholes leading to a malfunction [22]. Consequently, the production line from coating to stacking is usually positioned in a clean room with climate control at room temperature and a relative humidity of 50 % [270]. The in-line quality control of the coating surface of both CCM and GDL is also a critical issue, because both coating surfaces are highly relevant for the functionality and durability of PEMFCs [1,266,301]. In contrast to the CCM, the GDL shows a certain level of flexural rigidity, which needs to meet the requirement of roller design in a R2R-process. Due to the manufacturing process, the GDL often has anisotropic properties and a preferred direction with higher mechanical stiffness in the machine direction, which must be taken into account during subsequent stacking [89]. As the GDL carries

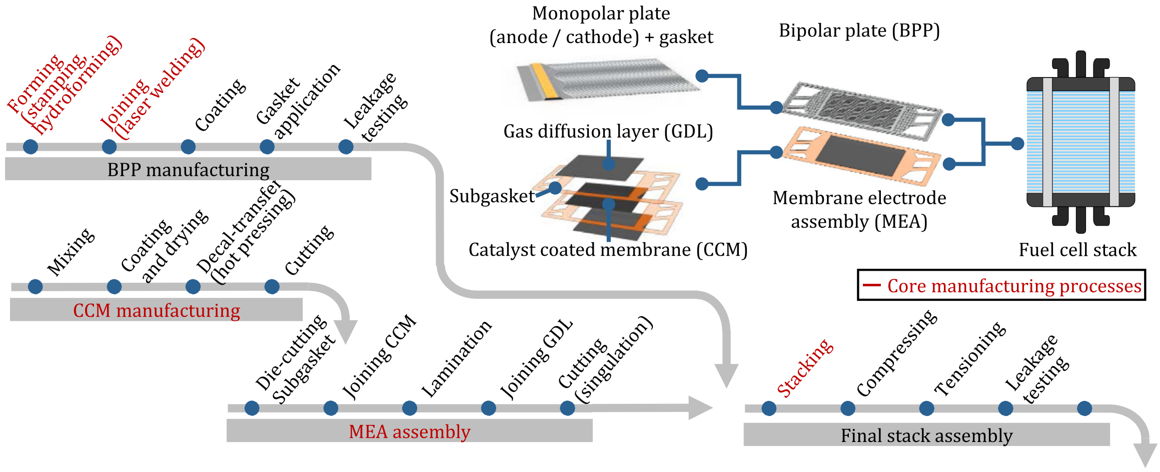

Fig. 6. Left: Process chain for the manufacturing of PEM fuel cells according to the industrial state-of-the-art; Right: Product structure of a fuel cell.

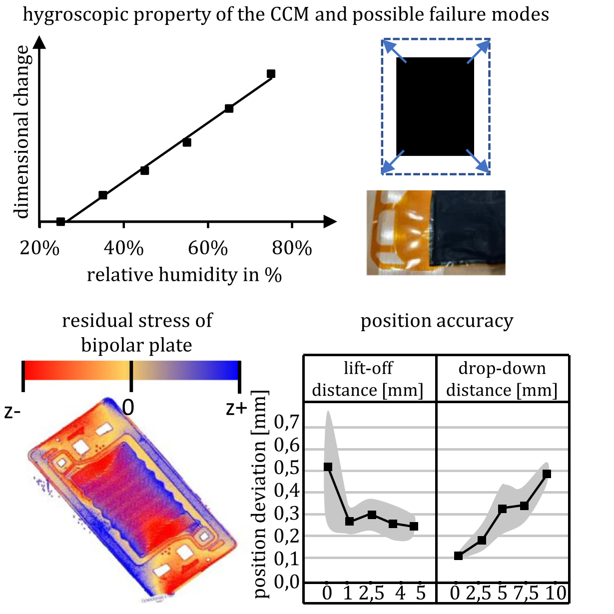

Fig. 7. Challenges and research fields in fuel cell manufacturing and assembly processes [159,222].

various functionalities, the interaction between multi-physical properties of the GDL, such as gas permeability, electrical and thermal conductivity, and the manufacturing process parameters must be considered and controlled to ensure the fuel cell performance [293].

The raw material for BPPs has evolved from graphite to metal in the past, but since the application of fuel cells in heavy-duty trucks are gaining more attention, graphite-polymer compounds are becoming attractive again [64,140]. Metallic BPPs which are often made of stainless-steel offer advantages in thickness and weight as well as in manufacturing due to advanced forming technologies, but require time-consuming coating and drying processes. On the other hand, graphite-based BPPs do not require additional coating but are volumetrically thicker and have a certain level of hydrogen permeability. Therefore, the graphite BPP is often preferred in stationary applications or heavy-duty trucks, where durability is more important than the size [199].

After stacking, the whole stack is compressed by a defined force to achieve a tight contact between sealing and subgasket. But moreover, a desired porosity of GDL and thereby an optimum mass transport and ohmic resistance should also be achieved, which makes the GDL the most sensitive component during this process. In this context, Han et al. have concluded that the so-called GDL intrusion effect can be suppressed if the machine direction of the GDL is aligned perpendicularly to the flow field direction [89].

3.2.3. Core manufacturing processes

The core manufacturing processes as main objectives of current research correspond to the function-dependent structure features of PEMFCs. Starting at the beginning of the process chain, the direct coating of the membrane is focused in research to reduce cost-intensive scrap of decal film and due to requirements on the installation space, although the decal coating process is already established. The technological trend in MEA assembly towards a continuous roll-to-roll process is also growing. The benefit of R2R processes in comparison to pick-and-place operations is not limited to the reduced process time [264]. In addition, the uncertainty in positioning accuracy is reduced compared to discrete gripping operations due to the limp characteristics of the CCM. Given the uncertainties of the market, the coexistence of a hybrid process chain, characterized by the incorporation of roll-to-roll, roll-to-sheet and sheet-to-sheet processes, is likely to endure in the foreseeable future, primarily to ensure the flexibility and the scalability of the manufacturing system. Corresponding to the active area, the flow field channels are the most important design feature of a BPP, with strict requirements on the channel dimensions (width, radii and depth). For better fuel flow distribution and water removal, a high aspect ratio of the channel height comparison to width is desirable, which can only be achieved to a certain extent depending on the employed material and forming technology [165]. In addition, a compromise is often required among manufacturing speed, material cost and achievable product quality. Similar to the MEA assembly process, this involves a continuous forming process through the roll-to-roll hot embossing process [25]. The most critical quality attribute for a fuel cell stack is gas-tightness. Therefore, the stacking process is of great importance [222]. Many factors can lead to stacking inaccuracy. BPPs, as one of the two repeating units of the fuel cell stack, often experience residual stress due to forming and joining processes and therefore show a bistable characteristic (see Fig. 7).

This characteristic should be handled carefully to avoid systematic failure. Furthermore, an imprecise stacking process, in particular when the sealings or the flow field channels are not stacked in the defined position, induces a shear stress on all MEA components, which accelerates mechanical degradation [111]. The gripping process must also be improved for damage-free handling to achieve a good quality [21]. The lift-off and drop-down distances have a particularly significant influence. For instance, when handling the limp CCM sheet, a higher lift-off distance is, counterintuitively, beneficial for achieving greater accuracy. This can be attributed to the curling-induced curvature of the CCM, which causes unevenness in its initial state prior to gripping (see Fig. 8) [222]. Moreover, a uniform compression and clamping force is critical for the durability of PEMFCs, as this assembly force becomes one of the long-term mechanical stresses on the components and can lead to mechanical degradation [238].

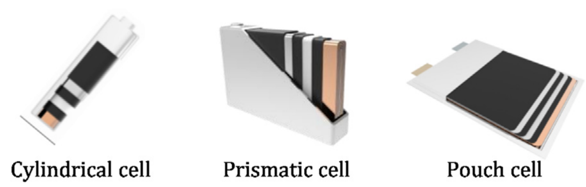

Fig. 8. Types of battery cells according to the state-of-the-art.

3.2.4. Analytical, numerical and data-based modeling approaches

The main modeling approach in the scope of research on fuel cell manufacturing processes is the finite element method (FEM). For example, the effect of membrane swelling on the fuel cell performance was analyzed in several studies [114,265]. In addition, the swelling-induced stress and strain during the MEA assembly process was also investigated by this approach [159]. In the context of BPP forming, the FEM was used to describe the formability of sheet metal to the complex flow field structures [17] and to inspect thinning areas critical for cracks [195]. The influence of the assembly force on the deformation of components, e.g., GDL-intrusion [38] or end plate deformation [29], was also analyzed by means of FEM. With focus on roll-to-roll processes, approaches can be transferred from related applications as manufacturing of flexible electronics and solar cells [71]. In addition, an analytical model was used to simulate tension inhomogeneity and critical wrinkling during MEA assembly – a guide to design the R2R transporting system [34].

3.2.5. Implications of product-specific trends on production

The manufacturing and assembly processes of fuel cells face several interconnected challenges as they develop into large cell areas for megawatt applications. A primary concern is maintaining precise control over the MEA production, where even minor variations in thickness or component alignment can significantly impact cell performance. The handling of delicate membrane materials during assembly poses particular difficulties, as these components are susceptible to damage and contamination. This is compounded by the need to achieve uniform compression across the cell stack while ensuring proper sealing and electrical contact. As manufacturers strive to scale up production, innovative handling and assembly technologies are required to meet the new challenges coming along with the technology [158]. These challenges are further complicated by the need to incorporate quality control measures throughout the production process without significantly impacting throughput rates [301]. This includes developing robust methods for stack assembly that ensure uniform compression and proper alignment of multiple cells while maintaining the integrity of each component.

4. Manufacturing of battery cells and modules

Battery cell and module manufacturing plays a crucial role in the advancement and production of innovative energy storage systems. The technologies used in the manufacturing processes significantly influence costs, energy consumption, and overall production efficiency, thus steering future research and development efforts [153]. In the realm of automotive battery packs, a common approach involves a pack-module-cell structure, while the battery cell format varies between round cells, prismatic cells and pouch cells (see Fig. 8).

Lithium-ion batteries (LIB) are a well-established cell chemistry in the automotive industry [142]. Independent of their format, LIBs consist of a composite of anodes, cathodes and separators, soaked by electrolyte and arranged in a housing including the electrical contacts. However, interconnecting the individual cells to form a battery pack poses several challenges. Firstly, it must meet mechanical stability and safety requirements, considering the exposure to dynamic loading and vibrations during operation. Secondly, there are chemo-mechanical challenges in cell manufacturing and thermo-mechanical challenges arising from the varying thermal expansion of dissimilar materials, which can result in deformation due to heat generation in battery modules [271]. Lastly, metallurgical changes such as fretting corrosion, metal oxidation, and the formation of intermetallic compounds can weaken mechanical strength and increase electrical resistance [305]. The digitization of battery manufacturing is essential to enhance efficiency and implement energy-saving strategies. Analytical and numerical modeling techniques are necessary to reduce the mean time to launch and optimize various aspects of battery production [259].

4.1. Process chain in automotive manufacturing systems

The manufacturing process for automotive battery cells and modules involves a series of interconnected stages that are crucial for achieving high-quality and efficient batteries. These stages encompass electrode manufacturing, cell assembly, cell finishing, module assembly and pack assembly. The core manufacturing processes mentioned in this section are marked in red in Fig. 9.

At the beginning of the process chain, raw materials are prepared. The quality and characteristics of these materials have a major influence on the battery performance and lifespan [152].

Electrode manufacturing is another important step, which involves fabricating cathodes and anodes. It starts with slurry preparation, where the cathode and anode material is mixed using electrochemically active materials like lithium iron phosphate (LFP) or lithium nickel manganese cobalt oxides (NMC) [142]. The active material, the conductive agent, a solvent and a polymeric binder are coated on thin aluminum (cathode) or copper (anode) current-collector-foil. Both are separated by a separator made of nonwoven fabrics or polymers, which is coated with thin ceramic layers. The coating process is followed by a drying process, which is used to remove the solvent in a continuous process sequence [153]. Roll-to-roll processes have gained prominence due to their ability to produce electrodes at high speeds with improved thickness uniformity and reduced material waste [161]. Afterwards, a calendering process is carried out to compact the material by top and bottom rollers. This creates a defined porosity and thickness. The next step is the slitting, where a separation of the wide electrode coil into smaller electrode coils is usually done by rolling knives. The electrode manufacturing ends with a vacuum-drying of the finished coil material. The drying process is necessary to remove residual moisture and solvents and takes up to 48 hours.

The first step in the cell assembly is the separation process, in which the electrode sheets are cut out of the coil by a laser or a die cutting process. The sheets are magazined and prepared for the stacking process, which is a critical step in battery manufacturing. It entails stacking cathodes, anodes, and separators, followed by packaging, the addition of electrolyte and sealing. Automated assembly systems have been developed to enhance productivity, precision and consistency. These systems make use of robotics and advanced control algorithms to optimize the stacking process, ensuring proper alignment and minimizing defects [7].

The assembly of battery modules and packs involves connecting multiple cells to achieve the desired voltage and capacity. Advanced interconnect technologies, including ultrasonic welding, laser welding, and conductive adhesives, are used to establish reliable electrical connections between cells [147].

Thorough testing and quality control procedures are essential to ensure the reliability and safety of automotive batteries. Advanced testing equipment such as battery cyclers, impedance analyzers, and thermal chambers are utilized to evaluate battery performance under various operating conditions [15].

4.2. Challenges on manufacturing processes and systems

The manufacturing process for EV battery cells and modules is a critical and complex aspect of the automotive industry. As the demand for EVs continues to increase, manufacturers encounter specific challenges in optimizing the efficiency, quality, and scalability of battery manufacturing.

One significant challenge lies in the availability and cost of essential raw materials for battery production, such as lithium, cobalt, nickel, and manganese. The global supply chain for these materials is complex and vulnerable to geopolitical and environmental factors leading to potential shortages and price volatility [217].

The manufacturing of battery cells and modules involves numerous complex steps that demand precise control, consistency and stringent quality control standards. The absence of standardized processes across different manufacturing facilities can result in deviations in battery performance and quality. It is crucial to characterize and test batteries at various production stages to identify and address potential defects or performance issues. To ensure consistent production, minimize defects, and optimize manufacturing efficiency, the implementation of robust process standardization, automation and development of reliable and efficient testing methodologies is essential [5,14].

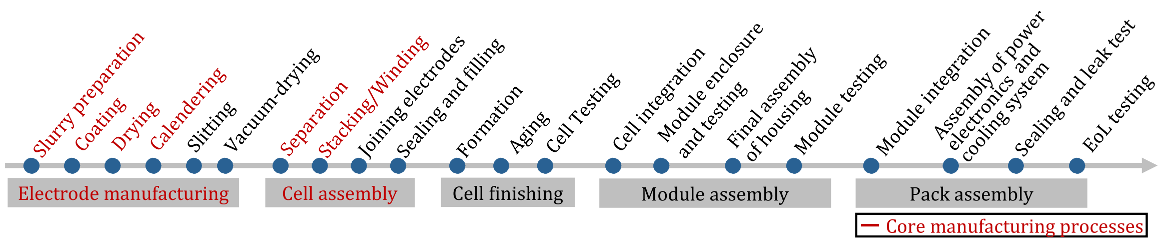

Fig. 9. Process chain for the manufacturing of battery cells and modules according to the industrial state-of-the-art.

With the increased demand for EVs, manufacturers are faced with the challenging task of scaling up battery production to meet market needs. Expanding production capacity while maintaining high-quality standards and efficient manufacturing processes is a complex effort. Manufacturers must invest in advanced production equipment and optimize their supply chains in order to achieve large-scale production [23,142].

With the increasing adoption of EVs, effective management of battery waste and the establishment of sustainable recycling processes are crucial. Developing efficient and environmentally friendly recycling technologies is essential for recovering valuable materials from end-of-life batteries and minimizing the environmental impact of battery manufacturing [217]. Implementing circular economy principles in battery manufacturing poses a significant challenge that necessitates collaboration among manufacturers, recyclers, and policymakers [208].

4.3. Core manufacturing processes

The manufacturing processes involved in battery cell and module production are of utmost importance as they significantly influence the overall performance and quality of battery systems. These processes are intricate and involve a series of steps that convert raw materials into fully functional battery components. This section provides an overview of the core manufacturing processes in battery cell and module production, along with the research fields contributing to their advancements.

4.3.1. Cell manufacturing

The initial step in battery cell manufacturing involves the preparation of positive (cathode) and negative (anode) electrodes, which is a crucial process. This stage includes the application of active materials, such as NMC or LFP for cathodes and graphite for anodes, onto current collector foils. Techniques such as slurry casting, doctor blade coating, and roll-to-roll (R2R) processing are commonly employed to ensure precise and uniform deposition of the electrode materials [155]. One important process step is calendering, in which the coating of the electrodes is compacted to a uniform thickness.

Cell assembly, a subsequent step, entails stacking the cathode and anode electrodes with separators placed in between. Various techniques, including stacking and winding, are utilized for different cell designs such as prismatic, cylindrical, and pouch cells. Stacking machines currently employ a Z-Folding process for the handling of the limp separator, folding a continuous separator web around the individual electrode sheets [116].

A novel stacking machine concept is presented in Fig. 10, which assembles cell stacks in a flexible and continuous manner utilizing an adapted Z-Folding process. Unlike conventional methods, this approach enables higher throughput and accommodates the production of battery cells in various formats. The system incorporates a flexible handling system and includes a dedicated bonding unit for the secure attachment of separators and electrodes. These components are subsequently directed to a folding unit, where the cell stack is constructed. To facilitate rapid adaptability, the system employs a digital twin, which supports quick machine reconfiguration in response to material changes and enables continuous process monitoring for optimization and quality control [117,118].

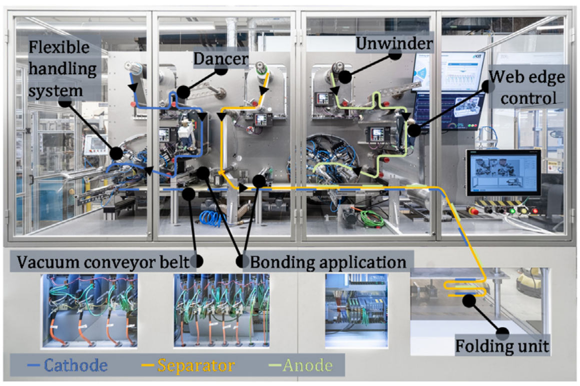

Fig. 10. New machine concept for a flexible cell stack assembly [117,118]. Image source: KIT, Bramsiepe.

In order to provide physical and electrical isolation of the cell, encapsulation processes like heat-sealing and ultrasonic welding are employed [45]. Another critical component of a battery cell is the electrolyte, which facilitates the movement of ions between the cathode and anode. The electrolyte can be in the form of a liquid, gel, or solid-state material. Manufacturing methods for liquid electrolytes often involve vacuum filling and injection techniques, while solid-state electrolytes require processes such as thin-film deposition and sputtering [36,102].

Ongoing research efforts continuously evolve the manufacturing processes for battery cells and modules. Two key areas of research contribute to these advancements. First, material science and engineering advancements drive the development of innovative electrode materials, electrolytes, and separators. These research endeavors focus on improving the energy density, cycle life, safety, and cost-effectiveness of battery components [144]. Second, research in manufacturing technology aims at enhancing process efficiency, scalability and reliability to increase throughput for large-scale production as well as reducing scrap rates. New battery technologies drive the need for developing new material compositions, which is only made more complicated by short development cycles. New materials are addressed in Section 8.2.

4.3.2. Module manufacturing

The production of battery modules involves the integration of multiple battery cells as well as the incorporation of additional components such as thermal management systems and electronic controls. To ensure consistent performance and optimal functionality, the cells are first sorted based on their electrical and performance characteristics. This sorting process includes tests for capacity, internal resistance, voltage, and cycle life [148]. The assembly of the modules entails arranging and connecting the battery cells in specific configurations, often in series and parallel combinations, to achieve the desired voltage and capacity. To achieve efficient and reliable module assembly, automated techniques such as laser welding, spot welding, and conductive adhesive bonding are used [47,147,248]. Maintaining proper heat dissipation is crucial for preserving optimal battery performance and longevity. To address this issue, thermal management systems such as cooling plates, heat pipes, and liquid cooling systems are integrated into the module structure. The manufacturing processes involve the attachment of heat transfer materials and the optimization of the thermal interface between the cells and cooling elements [77,289].

Tesla, as a pioneer in EV technology, has introduced an innovative cooling plate design for effective heat dissipation in round cell battery modules, incorporating phase change material for enhanced cooling efficiency [63]. In this context, analytic, numerical and data-based modeling approaches must be employed to systematically capture the complex relationships between manufacturing processes and the performance characteristics of battery modules as shown in the next section.

4.4. Analytical, numerical and data-based modeling approaches

The performance, reliability, and cost of battery cells and modules are strongly influenced by the manufacturing processes involved. Over the years, various approaches have been developed to model and simulate different aspects of battery manufacturing, including analytical, numerical and data-based methods.

Analytical modeling entails the use of mathematical equations and analytical models to describe and predict the behavior of manufacturing processes. These models are particularly valuable for understanding the underlying physics and chemistry in battery manufacturing processes, such as electrode coating, cell assembly, and module integration. For instance, Yang et al. proposed an analytical model to study the thermal behaviors of lithium-ion battery stacks during discharging, considering different cooling designs [293]. To analyze and improve the line performance of battery systems, analytical methods for integrated quality and production system analysis can be employed, focusing on productivity, quality, and associated bottlenecks [124].

Numerical modeling in the context of battery manufacturing involves mainly finite element analysis (FEA) or computational fluid dynamics (CFD) to enable a comprehensive understanding of process dynamics. For example, Kenney et al. [133] developed a physics-based simulation tool to estimate the effects of electrode manufacturing variations on the overall capacity, electrochemistry, and degradation of battery packs. Numerical simulation techniques provide valuable insights into the welding process by modeling and simulating the thermal, mechanical, and metallurgical phenomena involved. These simulations enable engineers to understand the effects of different welding parameters such as heat input and welding speed, on the final weld quality [40,180]. The mechanical deformation of the electrodes during the calendering process has a major influence on the following process steps, such as singulation and stacking [172] (see Fig. 11 left). To predict these cross-process influences, an FEA simulation model for the investigation of the stacking accuracy as a function of their shape is developed (see Fig. 11 right) [171]. By coupling various models of individual process steps, a digital process chain can be implemented, helping to better understand cross-process influences [275].

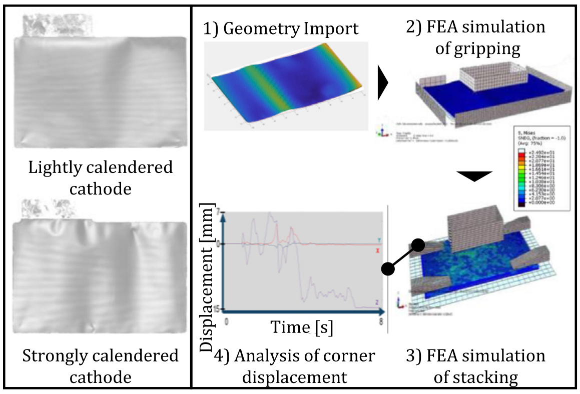

Fig. 11. Left: Influence of calendering on the cathode material; Right: Digital process chain using FEA simulation for cross-process influences on the stacking process [171,172].

In battery manufacturing, data-based modeling has gained prominence due to the increased availability of sensor data and advanced data analytics techniques. These models often utilize data generated by numerical models as a data source. Multi-output machine learning approaches for battery product design can be developed to predict final product properties using intermediate product features [263]. Therefore, it determines the necessary intermediate features to achieve desired process parameters and ensure the desired quality of the final product. Chianese et al. [39] use the supervised machine learning for automatic classification of weld defects in thin foil copper-to-steel battery tabs and managed to achieve a classification accuracy of 97.5 %. Thiede et al. propose a machine learning approach to systematically analyze energy efficiency potentials in the battery manufacturing process with a specific focus on electrode coating [256]. They note that these machine learning models are typically regarded as black box approaches and should be complemented by physical models. Singh et al. explored the functionalities of Digital Twin (DT) in battery systems and quantified the DT attributes across different life cycle phases [234]. Husseini et al. show a generally applicable method with which it is possible to generate a digital representation of the machine for the Z-folding process [116]. This allows the investigation of machine-related influences on the stacking process and to derive recommendations for action, which is particularly useful for the ramp-up phase [116]. Husseini et al. further developed a DT of a continuous and flexible cell stacking system [118]. It is shown that systems can be put into operation virtually with the help of DTs in order to optimize their ramp-up phases [105].

4.5. Implications of product-specific trends on production

An important trend specific to battery products is the demand for fast-charging capabilities to address the need for a rapid charging infrastructure and reduce EV charging times. Achieving fast-charging capabilities requires an optimized cell design and material selection as well as manufacturing processes to minimize resistance, to improve heat dissipation, and to ensure electrochemical stability during rapid charge-discharge cycles [53].

Safety considerations are of utmost importance in battery production, particularly for automotive applications. Product-specific trends focus on enhancing the safety aspects of battery cells and modules by incorporating advanced materials like solid-state electrolytes and fire-retardant separators as well as implementing robust manufacturing practices such as precise cell assembly and effective thermal management systems to mitigate the risks associated with battery failures [293].

Welding techniques are also crucial for ensuring the structural integrity of battery modules and packs. Strong, durable, and leak-proof connections between different components, achieved through welding processes such as resistance spot welding (RSW) and laser welding, are vital for the reliable and safe operation of batteries, especially when joining different materials such as aluminum and copper commonly found in battery modules [39,180,249].

Product-specific trends emphasize the development of eco-friendly manufacturing processes, including the use of recycled materials, reduced carbon footprints, and environmentally conscious manufacturing practices [297]. Implementing sustainable production strategies necessitates collaboration across the supply chain, incorporation of life cycle assessments, and adoption of circular economy principles (see Section 7) [175].

5. Manufacturing of power electronics

Power electronics convert electrical power between different forms, by altering voltage, current and frequency to meet load and source requirements. In EVs, power electronics link the direct current (DC) high-voltage (HV) battery with the alternating current (AC) traction motors. They are also used for charging the battery and powering auxiliary systems. This section primarily focuses on power electronic components that connect the HV battery to the motor in the electric drive system. However, the general setup and manufacturing processes apply to all power electronics, which must be selected and scaled based on specific needs.

While a power inverter used in EV comprises a range of different components, such as capacitances, gate driver boards, heatsinks and a housing, the most relevant component is the power module, which is the main focus of this section. The power module houses the semiconductor bare dies, which are used to realize the basic switching functions required for power conversion. The timing of the switching process is controlled by a gate driver board. The inductive and capacitive components are used to smooth the current or voltage levels as well as to realize a wide range of inverter topologies.

While a wide range of different interconnection technologies can be used in power modules, the general manufacturing steps are described based on a standard power module package, which is given as a cross-section in Fig. 12 [296]. Variations of such a package and

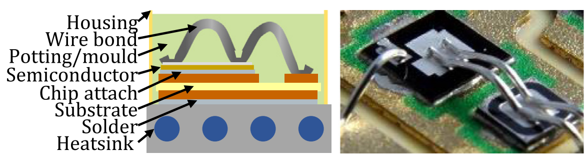

Fig. 12. Left: Cross-section of a standard power module package; Right: Direct bonded copper (DBC-) substrate with soldered chips and bonded Al wire loops.

trends towards improved manufacturing processes will be highlighted in the subsequent sections.

The power module's core functionality is determined by the semiconductor chips and their electrical topology. It serves as the electrical connection between the semiconductor chips and other components of the power electronics system, such as the battery or motor. These connections must have low inductance to minimize switching losses and ensure proper electrical isolation, especially during voltage spikes caused by switching load currents in inductive loads. The power semiconductors produce the bulk of the power losses in the module. Therefore, the power module has to function as part of the thermal management of the power semiconductors by providing a thermal path to the heatsink and sufficient thermal capacity to handle peak load conditions. The electrical and thermal interconnections must be reliable and withstand thermomechanical stress during operation. Moreover, the power module protects the semiconductor chips and interconnections from environmental influences such as dust, moisture, and chemicals. It also enhances mechanical robustness for ease of handling. The comparatively high requirements on thermal and electrical performance cannot be met with the state of the art in through-hole or surface mounting on printed circuit boards (PCB) while maintaining high power density, which is why the module design and manufacturing steps described in the following are required.

5.1. Process chain in automotive manufacturing systems

To meet the requirements of a standard power module, a design as shown in Fig. 12 is utilized, which necessitates a manufacturing process similar to the one depicted in the figure. The core manufacturing processes mentioned in this section are marked in red in Fig. 13. First, a substrate type has to be selected, onto which the semiconductor can be attached. Direct bonded copper (DBC) substrates as well as active metal braced (AMB) substrates are widely used in power modules. They consist of a ceramic isolation layer with a copper metallization on both sides. The ceramic layer typically consists of aluminum oxide (Al_2O_3) or silicon nitride (Si_3N_4), which provides good isolation properties while maintaining adequate thermal conductivity. The copper metallization layer on one or both sides of the ceramic layer is structured in such a way that it realizes part of the electrical layout of the power module.

The manufacturing of power semiconductor dies itself is outside the scope of this paper, further information on this topic can be found in Franke et al. [70]. These power semiconductors, which can be diodes as well as controllable devices such as IGBT or MOSFET, are mostly vertical components that provide the necessary current carrying capacity, requiring an electrical interconnection at the top as well as the bottom of the die.

To interconnect the chip's bottom side with the substrate, an interface material is required. Depending on the interconnection technology, different materials have to be used. If the semiconductor is to be soldered, a lead-free solder compound is used, while sintering is done using silver paste. These die attach materials are typically applied to the substrate by means of stencil printing of a paste or using pick and place for solid preforms. Next, the semiconductor itself is positioned on top of the interface material. If a solid preform is used, a tacking agent might be required to avoid shifting of the chip before the bottom side die attach process is completed. In a next step, the actual interconnection is formed. For a solder-based power module, this is done by applying a temperature profile specific to the combination of solder material and general thermal properties of the power module using a chamber-based oven. Proper die attach can only be achieved if there are no contaminations or oxidation layers at the intended interfaces. To reduce oxide layers on metal interfaces, flux can be added to solder paste or ink. Alternatively, soldering in a hydrogen-rich or formic acid atmosphere can be used. Vacuum or overpressure further minimizes voids in the solder layer [60].

If a higher level of reliability or better thermal performance is required, sintering will be used. The sintered interconnection is formed by applying a combined temperature and pressure profile using a sintering press. If a solder-based chip attach process is used, further components on the module layer, such as shunts or thermal resistors, can be applied to the substrate in the same process as the power semiconductors. In the case of sintered power modules, these components, which cannot be sintered, can also be integrated in a regular soldering process. If flux is used to reduce the oxide layers, an additional cleaning process might be necessary to remove residue, which can hinder subsequent joining processes or result in reduced breakdown voltage of the module [99].

After completing the bottom side interconnection, the substrate is soldered to a heatsink or baseplate using a temperature profile adapted to the higher thermal capacity of the heatsink. Then, the frame or housing of the power module can be attached. Typically, the housing is glued to the baseplate or heatsink. It can incorporate load terminals and signal interface pins.

The top side chip interconnection is achieved by heavy wire bonding with typically 100 µm to 500 µm thick aluminum wire. The interconnections are formed by sequentially bonding multiple wires to both the chip and the substrate. This process is a core manufacturing process and will be explained further in Section 5.3.

Wire bonding can be used to connect the chip to the substrate and also to link the substrate traces to the load and signal terminals of the module housing. Depending on the module package design and requirements, alternative processes such as laser or ultrasonic welding as well as soldering the terminals directly to the substrate, can be utilized.

After all internal electrical connections of the power module are formed, the module has to be encapsulated in order to improve the voltage ratings, prevent arcing at high voltages and protect the device from external environmental influences such as moisture, vibration and gases. Polymeric encapsulation with soft silicone gel by potting is the standard technology in packaging of frame-based power modules.

Another option is hard encapsulation with epoxy resins by potting or moulding. Especially large-area transfer-moulding of epoxy mould compounds has established itself within the last decade as it allows more complex module designs and has the potential for cost reduction compared to the standard soft potting approach within high-throughput production [239].

In order to control the semiconductor switches in a power module, a control board, integrating the gate drivers into the power

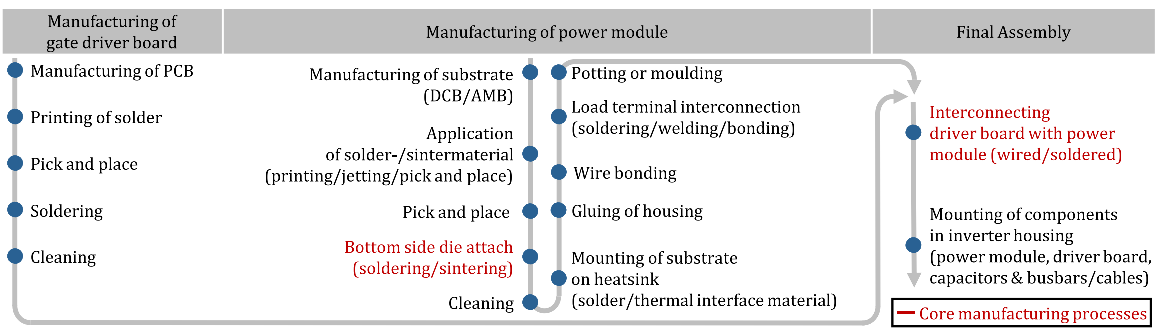

Fig. 13. Process chain for manufacturing of power electronics for EVs according to the industrial state-of-the-art.

inverter, is required. These gate driver boards often use PCB as a substrate since they require only moderate current levels but implement a more complex electrical layout, requiring multiple electrical layers to allow for a small package footprint. All required components are soldered onto the substrate by means of standard surface mount devices (SMD) or through hole devices (THD) processes [70,149].

The completed gate driver board is connected to the power module, either by connectors or soldering, depending on the positioning of the components in the power inverter, in the next step. However, in order to ensure fast switching capabilities, short traces between the gate driver and the power semiconductor chips are required. The module-driver assembly is mounted in the inverter housing in combination with power bus bars, capacitors and cooling circuitry, which completes the power inverter. At this point, it should be noted that the sequence of processes can be changed depending on the value added in each step and the respective yield and testing possibilities.

5.2. Challenges for manufacturing processes and systems

Minimizing scrap rates is vital for optimizing cost-effectiveness and overall yield, especially considering the expensive components used in power modules, since rework is often not possible or not permitted for automotive components. Ensuring consistent quality and reliability is crucial as well.

Manufacturers therefore strive to minimize variations in the manufacturing process, process influences must be carefully monitored and controlled and process outputs extensively tested. The selection of manufacturing processes should be based on the power density requirements and production volume, taking into account that most tools and processes need to be adjusted for each design change [50].

Power module manufacturing often requires a controlled cleanroom environment to minimize contaminants that can compromise module functionality and reliability. Proper storage conditions and protection against oxidation or moisture are essential for power module components, solder- and sinter-pastes might require storage at low temperatures. Power semiconductors are susceptible to electrical and mechanical damage during manufacturing. Manufacturing processes must therefore address these vulnerabilities and limit stress on the chip.

5.3. Core manufacturing processes

Since the packaging technology used to interconnect the power semiconductor is often the limiting factor with regard to reliability, achievable power density as well as safe thermal operation range, the interconnection at the top and bottom of the chip will be described in more detail in the following sections.

5.3.1. Top side chip interconnection

Ultrasonic wedge bonding is the state-of-the-art wire bonding process for power module manufacturing. It is a cold friction welding process in which the bond wire is pressed onto the bond interface, which could be the power semiconductor, the substrate or load terminals in the housing. The bond contact is formed by applying mechanical oscillations in the ultrasonic range as well as a bond force normal to the target surface to the bond wire using the bond tool. The bond tool is then moved along a trajectory above the substrate to form the intended bond loop geometry and desired amount of bond contacts.

Since the increasing power loss density in the bond wires results in a reduction of the lifetime of the power module [236], a change of the wire bond material from aluminum to other materials such as copper can bring forth a more reliable power module for applications with high current and power density. Due to the higher Young's modulus and lower plasticity of the copper bond wire compared to the established aluminum bond wire, new challenges arise. The required higher bond force and ultrasonic power can potentially damage the fragile power semiconductor [127], since it is only protected by a thin aluminum metallization layer. This aluminum layer serves as an interface between the top side chip interconnection and the semiconductor and distributes the load current across the whole area of the chip. This layer also degrades over time, leading to lower current density distribution in the chip itself [235]. In order to enable a top side interconnection technology, which induces higher mechanical stress on the chip during manufacturing, as well as to ensure proper utilization of the chip, additional copper metallization layers on top of the die are used. These layers can be manufactured by using established metallization processes, sintering a thin copper foil or additively, using cold spray plasma [191]. An alternative option also providing higher current carrying capabilities, but with reduced geometric freedom regarding the loop formation, is a further increase of the cross-section of the bond wire by switching to a rectangular bond ribbon instead of round bond wires. Since the stiffness of the bond ribbon depends on the direction of bending, this imposes additional challenges on the bond process. Ribbon bonding can be carried out using aluminum as well as copper ribbons, with the latter facing additional challenges regarding the cutting process, requirements for increased chip metallization stability and wear of the bond tool [167]. Likewise wire bonding soldered or sintered metal clips on top of the chip can also be used [216].

5.3.2. Bottom side chip interconnection

While the solder and silver-sinter processes for manufacturing the bottom side chip interconnection are already established, further improvements to reliability as well as thermal performance are still the focus of ongoing research. Thermal performance of a soldered interconnection depends on the number, size and location of voids in the interface layer [194], which is why contamination-free surfaces and adequate oxide removal as well as the avoidance of gas entrapment have to be ensured.

Soldered chip interconnections are operated at a comparatively high homologous temperature, which results in a limited lifetime due to delamination and voiding. This can be avoided by using more robust solder composites or switching to a sintering or diffusion soldering process. In order to achieve even higher reliability and higher cost-efficiency, a copper based sintering process can be used instead of silver-sintering [226]. Additionally, pressureless sintering is being investigated as an option to reduce process complexity as well as stress on the joining partners due to otherwise high pressure requirements [227].

Besides sintering, diffusion soldering is an alternative interconnection process which is also stable at high temperatures [193]. The diffusion solder material consisting of high as well as low melting metals like copper and tin is used as paste or preform. During the soldering process, the low melting solder material is transformed completely into intermetallic compound phases by diffusion, the remelting temperature of these phases is higher than soldering temperature and higher than the melting point of common Sn-based solder alloys [251]. The combination of high interconnection reliability, low process complexity and the use of standard reflow soldering equipment for diffusion soldering have the potential to decrease the costs for high temperature proof die attach interconnections.

5.3.3. Substrate

Further optimization of DBC and AMB substrates is achieved by variation of the layer thicknesses towards thicker copper and thinner ceramic layers. This comes with the added challenge of increased warpage during further processing as well as reliability issues during thermal cycling resulting in cracks in the ceramic layer. Besides these established substrates, which are mainly suitable for large volume production and feature a simple planar metallization structure, other technologies are evaluated as alternative for high power density applications or complex substrate geometries.

Laser powder bed fusion of metals (PBF-LB/M) is an additive manufacturing process, which utilizes a focused laser beam to locally fuse metal powder, which is applied layer by layer, according to a geometric model without product-specific tooling [78]. The process allows for a high freedom of design for complex parts like heatsinks with integrated cooling channel, enables cost efficient production of customized products in small lot sizes [246] and accelerates the development process due to accelerated lead times. Current research is also focusing on optimization of adhesion between copper and ceramic by promoting material-bonded adhesion mechanisms as well as proper coupling of the laser to ensure adequate power density in ceramic and metal powder [278].

Cold atmospheric plasma metallization (CAPM) is a 2D additive manufacturing process, which uses argon plasma as an energy source to melt and propel copper particles onto a ceramic surface [107]. For thin metallizations (<200 µm), the CAPM technology could be established as an alternative process to conventional substrate manufacturing technologies, Similar to the PBF/LB-M approach, resource intensive etching procedures can be avoided.

5.4. Analytical, numerical and data-based modeling approaches

Power modules consist of a multilayer structure of different metal, ceramic, semiconductor or polymer layers that are combined to ensure the desired electrical and thermal functionality. As the incorporated materials have different mechanical and thermal expansion behavior and large joint faces occur, temperature changes in manufacturing and assembly lead to thermo-mechanical stresses, often resulting in significant warpage of the components and the whole assemblies. Therefore, several simulation approaches are used to reduce the time required to design a power module and to set up and monitor the manufacturing processes.

Multiphysics finite element (FE) simulations are performed to evaluate the stresses of the interconnections in a power module. The wire bonds as well as other interconnections on the power semiconductor are susceptible to thermomechanical stresses during operation. The FE simulations are used to evaluate these stresses depending on a selected design within the available process window of the bonding machine and correlate the stress levels with the expected lifetime based on accelerated lifetime testing [237]. Thermo-mechanical simulation are used to optimize module design, materials and process parameters with respect to assembly warpage [240].

Data-based modeling is used for lifetime and reliability predictions of new power module designs. These predictions are derived from a large number of durability tests, but require considerable time and material expenditure [18]. Process monitoring based on machine learning models is primarily used in the field of PCB components manufacturing such as the gate driver board. These models can support adequate predictive maintenance of manufacturing equipment as well as avoid unnecessary testing of components due to false classification of a potential defect [254].

In addition, when using high viscosity potting or molding materials, encapsulation or mold flow simulations can help reduce air entrapment by optimizing the dispensing strategy [244] or mold design and mold parameters as well as module design [295]. It has to be noted that simulations concerning the manufacturing process are always based on simplified models. Influencing factors such as oxidation layers or contamination often cannot be included in such simulations. Fig. 14 illustrates an exemplary study on the influence of encapsulation materials on the lifetime of bare die interconnects within power modules with regard to the change in fatigue behavior, the forward voltage and the number of survived power cycles as a function of the thermomechanical stress build-up through the encapsulation [241].

5.5. Implications of product-specific trends on production

The shift towards wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) indicates a potential transition from the long-established standard of silicon-based power electronics. These materials offer advantages such as higher efficiency, faster switching speeds, and better thermal performance compared to traditional silicon-based devices [122]. The adoption of SiC and GaN in power electronics increases the requirements on the power module package performance. In order to fully utilize the potential of these wide bandgap semiconductors, new power module packaging materials and package designs, such as double-side cooled power modules or designs with chips embedded into the substrate, might be required [112,296]. These types of design change the manufacturing process and technologies, wire bonding might become less relevant as sintered interconnections on both sides of the chip come into focus. For the more distant future, ultra-wide bandgap semiconductors such as aluminum nitride (AlN) show further promising potentials.

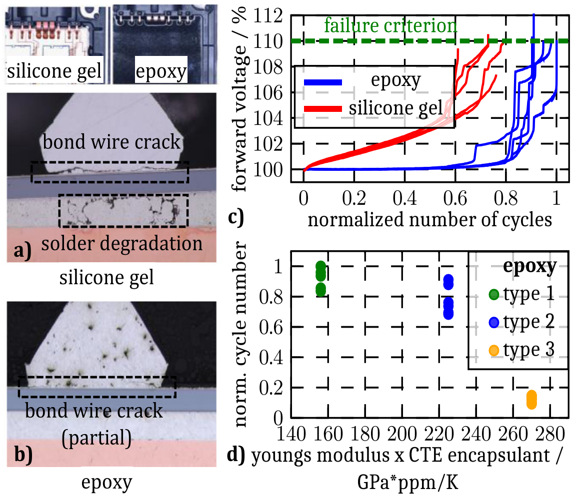

Fig. 14. Influence of encapsulation materials on lifetime of bare die interconnections in power modules with a decrease of solder layer fatigue (a & b) and a lower forward voltage slope resulting from reduced metallization reconstruction on bare die surface (c) when switching from standard soft to epoxy-based hard encapsulant as well as a reduction of survived power cycles with increase of stiffness and thermal expansion properties of the used hard encapsulant (d) [241].

6. Manufacturing of electric traction motors

The electric traction motor converts battery energy into kinetic energy using magnetic forces. It consists of a stator, rotor, housing, and transmission. The main motor types use a three-phase stator to create a rotating magnetic field. While multiphase drives improve torque distribution, they are not widely used due to complex modeling, control, and manufacturing [73,219]. Common motor types include induction motors (IM), permanent magnet synchronous motors (PMSM), externally excited synchronous motors (ESM), and synchronous reluctance motors (SRM) [2,28,81,200].

For electric motors, which are used in hybrid or all-electric drivetrains, the power density and the efficiency are crucial. Due to the limited installation space, the electric motor must be as compact and light as possible [86]. For these reasons, the most common topology is the PMSM, with a stator similar to that of IM and ESM. In ESMs, permanent magnets in the rotor are replaced by a wound rotor. In automotive applications, interior permanent magnets (IPM) are preferred for better performance at speeds above 15,000 rpm. The rotor of an IPM consists of 3–8 lamination stacks including hundreds of magnets in various arrangements. IPMs offer high reluctance torque, efficiency, power factor, low heat, compact size, and low noise. With cost-effective power electronics, they dominate traction motor applications. IPMs are maintenance-free, with minimal wind friction losses and very low noise [28].

The transmission is not considered in the following, because knowledge from conventional transmission design can be applied – despite the high speeds and low number of gears compared to combustion engines [228]. In today's electric vehicles one or two gear transmissions are state-of-the-art.

The automotive industry's demand for high-volume, low-cost production has led to improvements in winding technologies. Conventional round wire winding is replaced by insulated rectangular copper wire, forming 3D hairpin coils. A hairpin stator for an electric traction motor contains different types of coils for layer and phase

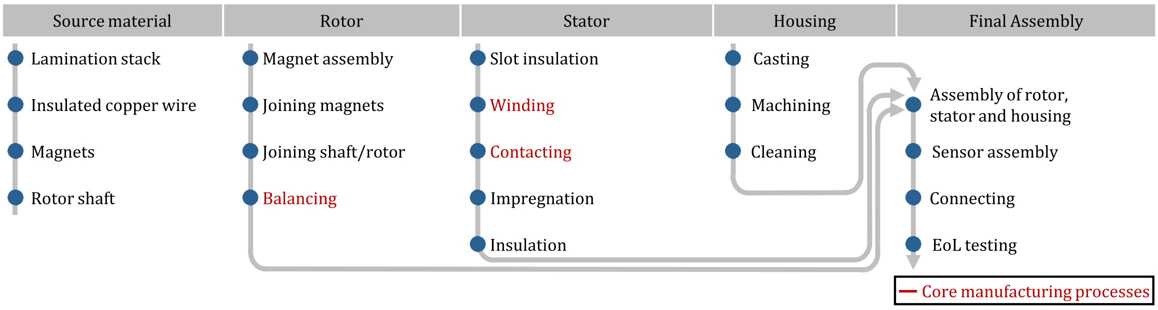

Fig. 15. Process chain for manufacturing of electric motors with permanent magnets according to the industrial state-of-the-art.

connections. A hairpin stator for an electric traction motor contains at least one type of hairpin coil per layer, one type per layer for connection and three types for the phase connection. Hence, up to 720 hairpins are inserted in a stator with its 36–120 slots and 4–8 layers. Thereby, technical boundary conditions such as installation space, electric, thermal and mechanical interfaces, performance and operating behavior as well as economic constraints were considered. The product structure of a PMSM is shown in Fig. 16 [33,88].

6.1. Process chain in automotive manufacturing systems

The manufacturing process chain depends on the motor topology to be produced. Nevertheless, the overall process chain can be separated in the upstream manufacturing of source materials, that need to be prepared for stator, rotor and housing manufacturing. Fig. 16 illustrates the process chain for the manufacturing of PMSMs. The core manufacturing processes mentioned in this section are marked in red in Fig. 15.

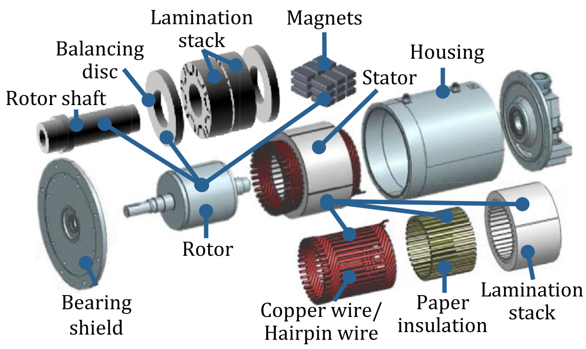

Fig. 16. General product structure of a Permanent Magnet Synchronous Machine. Image source: wbk.

6.1.1. Basic components

Regardless of the topology, rotors and stators are made of lamination stacks, consisting of electrical sheets with organic or inorganic insulation coatings to reduce eddy current losses. In automotive applications, these sheets are typically made of silicon, cobalt, or nickel-iron steel alloys, manufactured as cold-rolled strips. For inverter-fed motors, non-oriented steel with 2–3.5 % silicon is used [97]. Typically, the thickness of the electrical sheets and the insulation coating are limited to a range of 0.20–0.35 mm and 1–4 µm respectively due to the costs of manufacturing and the complexity of handling for core building [97].

To manufacture the characteristic stator and rotor design of each lamination, usually progressive dies or a punching die are used [303]. The air gap between the rotor and the stator is 0.5–0.8 mm and is considered in the manufacturing of the lamination stack. The application of laser cutting is limited to small series due to manual sheet and package handling [143]. As joining techniques of the electrical sheets in axial direction, interlocking, welding, clamping, and bonding are used [223,243,245]. As an alternative joining technology, twin roll casting for the casting process of electrical steel is investigated in research [183].

Moreover, enameled wire with a round or rectangular cross-section is a key component for the stator of each electric motor and the rotor of ESMs [110,283]. In automotive context, the conductor is made of the highly conductive copper types Cu-ETP, Cu-OF, Cu-OFE by drawing, rolling or continuous extrusion depending on the cross-section as well as requirements on quality and costs. The shaping of the conductor is followed by a cleaning process to prepare the surface for the application of the enamel.

This primary insulation coating consists of a primer followed by several layers of base and top coatings for dielectric strength and chemical resistance. According to the state of the art the thermosetting polymers polyesterimide (PEI), polyamide-imide (PAI) and polyimide (PI), but also high performance thermoplastics such as polyetheretherketone (PEEK) are used as coatings [79,86].

Permanent magnets in PSM rotors, typically NdFeB, are coated with epoxy or nickel for corrosion protection. Due to their brittleness, a joining gap allows force-free insertion, usually using non-magnetized magnets before downstream magnetization. To secure magnets and prevent vibrations, fixation methods include gluing, transfer molding, and caulking.

6.1.2. Rotor manufacturing

The PMSM rotor process chain includes magnet assembly, axial magnet insertion, joining of the shaft and lamination stack, and final balancing [250]. Depending on the rotor shaft-hub connection type, e.g., cylindrical interference fit or feather keys, the rotor shaft area is designed to ensure torque transfer. The rotor shaft is manufactured by turning or a combination of forming and cutting to meet high coaxiality demands. The hollow shaft, designed for weight reduction and cooling, is made by drilling, turning, or forming. Alternatively, assembled shafts are used. Manufacturing must ensure coaxiality of bearing seats and shaft sections, as well as proper lamination stack positioning [132,288].

6.1.3. Stator manufacturing

The manufacturing of stators is based on a sequence of forming, joining and assembly processes. First, slot liners which consist of several layers of aramid and imide polymers are inserted into the slots of the lamination stack as a secondary insulation as well as to prevent the winding from mechanical damages during insertion [113,170,247]. The manufacturing of the windings can be categorized into direct and indirect methods, depending on whether the coils are wound directly onto the lamination stack or prefabricated on auxiliary tools and then joined with the lamination stack [33,86,88].

Four conventional round wire winding technologies relevant for automotive stator and ESM rotor manufacturing are linear, needle, trickle, and insertion winding. Due to geometric constraints, the mechanical fill factor is limited to 90.7 %, restricting the electric fill factor. As a result, the electric fill factor as ratio of the conductor area and the total slot area is also limited. To optimize round wire winding processes [202], the tensile force and wire positioning in particular need to be controlled [110,151,201].

To maximize the electrical fill factor, rectangular wire windings dominate in electric traction motors. Hairpin technology, now standard in the automotive industry, enables high automation, productivity, and process stability. Hairpins are formed from rectangular wire using sequential or kinematic bending, arranged in tooling, and axially inserted into lamination slots. Their open ends are twisted circumferentially and laser-welded for series connection. Regardless of winding technology, stators undergo dip or trickle impregnation after winding assembly [209]. The impregnation is necessary to improve the durability, but is not primarily used as further insulation. However, the impregnation has a significant influence on the thermal behavior of the winding which limits the continuous power [141,205].

6.1.4. Housing manufacturing

The housing maintains the mechanical integrity of the stator, rotor, and gearbox. To save space, it is often integrated with the gearbox and includes cooling structures for heat dissipation. It features high-voltage terminals and sensor sockets for rotor position and temperature monitoring. In large series, aluminum die casting followed by machining and cleaning is usually used. High coaxiality requirements for the bearing seat and stator housing pose challenges. Additional components may be manufactured similarly and assembled to form closed cooling structures.

6.1.5. Final assembly

After manufacturing the base components, the stator is mounted in the motor housing, and the rotor is inserted. Additional modules like the gearbox or power electronics are integrated for compactness. The stator is joined to the motor housing using heat shrinking to prevent lamination stack deformation, with adhesives or welds for added safety. After magnetization, the rotor is axially inserted into the stator with precise coaxial guidance to ensure contactless joining due to the small air gap and strong magnetic forces. Each motor undergoes an end-of-line test using integrated or external power electronics to determine its performance curve and efficiency. Typical characteristics tested include speed, torque, friction losses, cooling circuit tightness, stator winding electrical properties, and high-voltage and insulation tests as well as noise, vibration, and harshness (NVH) behavior.

6.2. Challenges on manufacturing processes and systems

Considering the high number of individual parts of an electric motor, the assembly of an electric motor leads to many different manufacturing processes, all of which have to be handled within a tight tolerance. Electric traction motors are therefore manufactured in highly automated production facilities.

In addition, the highly complex individual processes require extremely high process control and stabilities, hence their optimization is the core of current research and development. For manufacturing stators on a large scale and achieving high-quality results with minimal cycle times, the hairpin technology represents the current state of the art production technique. The process chain involves a series of five sequential steps: shaping (straightening, stripping, cutting and bending of enameled rectangular copper wire), joining (slot lining of stator slots as well as composing and inserting of hairpin coils), twisting, contacting and insulating [210].

6.3. Core manufacturing processes

Due to material inhomogeneities as well as variations in manufacturing and assembly operations, each individual rotor requires a balancing process to achieve a balancing quality of about G2.5 which corresponds to an eccentricity of a few micrometers [197]. Balancing reduces vibrations and increases rotor lifespan. It can be done by subtractive (removal) or additive (material application) mass correction. Subtractive balancing offers higher operational safety, as no applied mass can detach, but requires an additional component like a balancing disk. Research is focused on selective balancing, which involves measuring unbalance and selectively mounting lamination segments, as well as positive unbalancing [169,287,288].

In order to maintain the required balancing quality at high operating speeds, a spinning process is sometimes integrated in series production to provoke settling effects by short-term operation above the operating speed. Since the spinning process is decisive for the entire rotor production in terms of costs and cycle times, the goal is to possibly avoid it. The spin test can be avoided by optimizing the rotor design or optimized assembly strategies.

The bending process can be identified as a core process of the stator manufacturing. Especially, the spatial bending of hairpin coils as the initial step has a significant influence on the downstream manufacturing processes [211,283]. Since the processes are linked to each other, the contour accuracy of the coils after shaping affects the reliability of the consecutive composing, inserting, twisting and contacting processes. In contemporary industrial applications, two different approaches are used for the shaping of hairpin coils and need to be differentiated due to a varying sequence of characteristic forming operations: tool-bound, sequential tool-bound and kinematic bending processes [286].

Sequential axial insertion of hairpin coils into the lamination stack is impossible due to mutual overlaps. Therefore, hairpins are preassembled in layers or segments and inserted as a whole. For increased robustness of the insertion process and to protect the insulation paper from damage, a mask is set on the lamination stack during insertion. To prepare the stator in its wave-like winding patterns the hairpin ends need to be twisted. During the twisting process the free wire ends are formed with stator-specific tools [66].

In order to enable a fast ramp-up for new wiring schemes, a kinematic twisting process is developed in research, which is shown in Fig. 17. This new machine concept uses a conventional industrial robotic system with a 3D-printed twisting tool. This tool manipulates the hairpins sequentially to manufacture the twisted contour of the hairpin stator which is necessary for the contacting process afterwards [95,96].

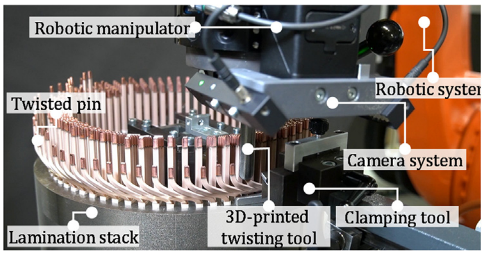

Fig. 17. New machine concept for the twisting process implemented with a robotic system [95,96]. Image Source: wbk.

The contacting process of the insulated copper conductors is one of the most challenging process steps. Although there are numerous technologies established for creating contact in electronics and electric motor production such as ultrasonic, resistance, electron beam welding and soldering [229], laser welding is almost exclusively used because of short cycle times, minimum heat coupling and non-contact operations. In the context of laser welding, there are significant interdependencies with the upstream stripping of the rectangular wire by machining or laser ablation [6,80,229,302].

To ensure the highest quality during the contacting process, camera-based monitoring as well as other optical measurements [90] in combination with machine learning methods are objective of current research [9,173,274]. Data-driven monitoring and real-time error detection are therefore of the highest relevance [174,272,273].

6.4. Analytical, numerical and data-based modeling approaches

In order to consider the high dependency on the specific design of the hairpin winding during manufacturing, digital process chains for production-oriented design were developed [66,94]. These approaches enable an optimized winding head geometry [94]. Finite element simulations were used to analyze the impact of forming on the insulation coating and develop concepts for improved process robustness, despite varying material characteristics [94,174,281–285]. Therefore, approaches for adaptive compensation of springback [41,284,285] were implemented based on material and defect investigation [277,292].

Fig. 18 illustrates data-driven approaches to optimize the hairpin bending process using simulation and modeling. Geometric wire models assist in path planning and collision detection during the twisting process, preparing the stator for the subsequent contacting process.

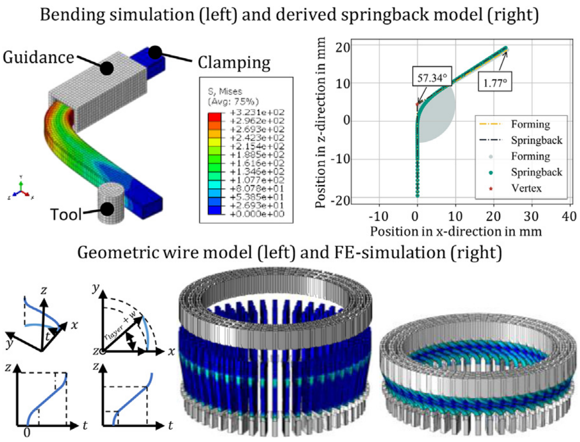

Fig. 18. Top: Bending simulation and derived springback model according to Wirth et al. [284]; Bottom: Model-based parametrization and FE-simulation for the twisting of stators with hairpin winding [96].

With the focus on hairpin stators, the laser welding process can be monitored by various process-accompanying sensor systems. These include camera-based vision systems, optical coherence tomography (OCT) or plasma sensors [9,90]. Furthermore, an approach for detection of potential insulation defects with machine learning is known [173]. Fault classification of the winding using augmented methods are part of the research (see Fig. 19).

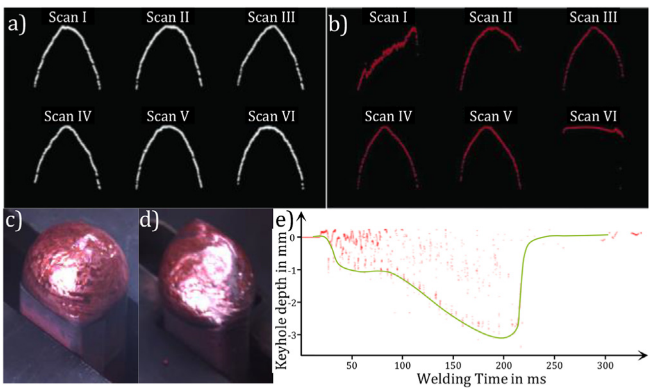

Fig. 19. Process quality control of the laser welding process using OCT scans and images with post-process OCT surface scans of OK (a) and NOK (b) samples, post-process images of OK (c) and NOK (d) samples and an OCT in-process keyhole depth measurement (e) [9,206].

6.5. *Implications of product-specific trends on production*

With regard to the topologies of electric traction motors, axial flux machines (AFM) are expected to become more relevant in the next generation of traction drives. The main benefits of AFM are a compact axial design combined with higher torque density compared to similar radial flux machines. Regarding the designs and topologies of AFM, there is a large variety, which also has a major influence on the production technologies used. For this reason, a definitive design has not been established yet and great efforts are being made in research and development in this area [8,129,186,220]. Wheel hub drives in EVs are also considered in research and development and pose their own specific challenges. Furthermore, EV applications with ESM machines gain momentum due to the global rare-earth permanent magnet supply situation.

As outlined in the last four component-specific manufacturing sections (see Sections 3–6), manufacturers encounter multiple complex technological challenges. Consequently, further research is required to address these technological hurdles effectively. When developing and working on these new technical solutions, LCE should already be applied in the early stages of the development process. The distinct demands for LCE in the context of e-mobility will be discussed in section 7.

7. Life cycle assessment and life cycle engineering

In order to determine the overall environmental superiority of e-mobility compared to mobility based on internal combustion engines, it is crucial to consider the entire product life cycle. Therefore, life cycle assessment (LCA) methodology is normally used to measure the environmental impacts of products and also to assess alternative vehicle concepts. The LCA methodology is based on four steps: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment, and (4) interpretation [48]. The life cycle perspective enables the comparison of different products and processes, which provide the same functional unit, and avoids burden shifting between different life cycle stages. The assessment of several environmental impact categories such as climate change and toxicity also avoid the shifting of burdens between environmental impact categories. The results also allow to identify significant mitigation levers in the foreground system (BEV or FCEV) or in the background system (e.g., electricity mix).

There are major differences when comparing the cradle-to-grave life cycle of an ICEV and EV. Fig. 20 schematically shows the environmental impacts of a BEV and an ICEV over their life cycles. The figure is divided into three parts: production spanning from raw material extraction, manufacturing to vehicle assembly, usage and end-of-life. The production stage of a BEV has a larger environmental burden compared to an ICEV, primarily due to the significant impact of battery production. The battery is responsible for 40–60 % of the GWP manufacturing impacts of the EV [150]. Within the battery, the raw material extraction and processing are the largest contributor to the environmental impacts with >50 % of the greenhouse gas emissions [181].

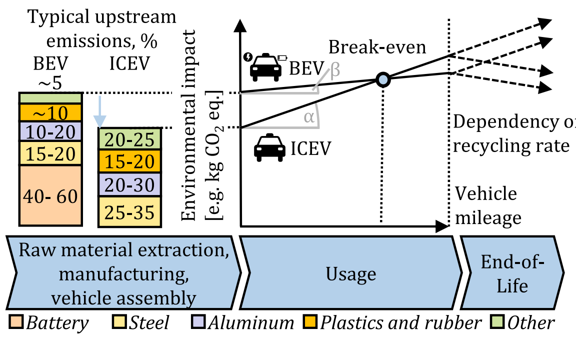

Fig. 20. Generic break-even analysis showing cumulative environmental impact over the vehicle lifecycle [31,150].

Throughout the vehicle's operation, the predominant environmental impact is primarily determined by fuel consumption (for ICEVs) or electricity (for BEVs). The slope of the curves, denoted as α and β, represent the environmental impact generated per kilometer driven. The break-even point indicates when the environmental benefits of an EV surpass those of an ICEV. If electricity generated from renewable energy sources is used for charging the BEV, near CO2-neutral vehicle operation can be achieved ($\beta \sim 0$), resulting in an earlier break-even. The same applies for FCEVs, which depends on a carbon-neutral hydrogen economy.

While in the past LCA was mainly applied to identify and quantify the environmental impacts of products, recently it has been used increasingly as a tool for decision making and engineering. The shift can be described as life cycle engineering (LCE) [32,92]. There are various definitions of LCE. Hauschild et al. [92] see LCE as an extension of LCA by defining it as "sustainability oriented product development activities within the scope of one to several product life cycles". Here, LCA is a fundamental part of LCE since it provides the quantitative appraisal of the environmental impacts of the engineered product (including sold volume and technological development) with the goal to support the focusing of the LCE activities [130]. This systematic approach can also be used to analyze different mitigation strategies and measures. The use of lightweight materials for instance is a common strategy which can simultaneously reduce the weight of vehicles and energy demand and therefore, ultimately decrease the environmental impact during the vehicles' use stage. If the use of lightweight materials is associated with higher environmental impacts from raw material extraction and manufacturing, the savings in the use stage have to outweigh these higher environmental impacts [108].

In EVs, lightweight materials can have the same effect as in ICEVs. However, different parameters (e.g., the electricity mix used for charging) determine how lightweight EVs perform in comparison to a reference vehicle [54]. E-mobility must therefore always be viewed as a system consisting of infrastructure (electricity or hydrogen) and electrically powered vehicles (battery or fuel cells). Compared to ICEVs, the LCA and LCE of EVs are more challenging. One significant reason are the inherent variations in the real world that affect the assessment results [115]. The environmental impacts of EVs are influenced by a large set of influencing factors in both the foreground system (e.g., battery size, battery chemistry, manufacturing scenarios) and the background system (e.g., electricity mix, local climate or weather) [54]. Three different types of variability must be distinguished: (1) temporal variability (e.g., seasonal changes in temperature effecting the energy demand for heating and cooling, changes of the electricity mix over the vehicle lifetime), (2) spatial or geographical variability (e.g., electricity mix or production routes of hydrogen in different regions), and (3) inter-individual variability of the users (e.g., driving style) or technologies (e.g., battery cell chemistry) [32,93].The consideration and transparent communication of variability is important for target-oriented product and process development of EV technologies [32,54,115].

7.1. Power supply systems

As in Section 3, Charging systems are first discussed in 7.1.1 and LCA and LCE in the context of fuel cells in 7.1.2.

7.1.1. Charging systems

As discussed in Section 3, stationary and dynamic charging systems can be distinguished. Kabus et al. [126] present a comparative LCA comparing AC-based on-board charging (OBC) with a charging power up to 22 kW with a DC-based off-board charging (OfBC) with 50 kW charging power (including an OBC with 3.7 kW charging power for charging at home). The study differentiates between charging infrastructure (connection with the grid, charging cable, housing of the charging station) and chargers (power electronics including housing). The production processes are modelled based on mass using Ecoinvent database, data from suppliers and literature. With focus on the production stage and climate change, the study shows that the production of the power electronics is the hotspot for both charging systems (see also Section 7.3). In the DC system (OfBC), the environmental impacts of the charging infrastructure are more significant compared to those of the AC system. In an AC system (OBC), the filter and the DC-DC converter are contributors. In the DC system (OfBC), the filter is the hotspot. For the filters, the inverter-side coils are most relevant. In the DC-DC converter, the coils and transformers are the components with a major influence on climate change but also the other impact categories reported, e.g., mineral resource depletion. The authors also investigate the effects of market diffusion concerning vehicle stock and charging infrastructure in Germany. The results show that DC charging is beneficial from an environmental perspective, with benefits increasing as the EV stock grows [126].

Balieu et al. present an LCA study on road types supporting dynamic charging [13]. A traditional asphalt road is compared with a conductive rail system, a conductive pantograph system and a wireless inductive power transfer (IPT) system. While the first two dynamic charging systems are mainly suitable for trucks, the IPT system can be also relevant for EVs. The IPT system is based on prefabricated concrete blocks with embedded copper coils. The reported CO_2 emissions associated with the construction are 45 % higher compared to the construction of the traditional asphalt road. The study also highlights that road maintenance and winter operations add additional environmental burdens [13].

7.1.2. Fuel cells

Recent developments in fuel cell production focus on lowering costs and improving manufacturing efficiency. A key strategy is to reduce or completely avoid the use of expensive materials. This often goes hand in hand with a reduction in potential environmental impacts. Garraín et al. [74] highlight the significance of raw material extraction and the manufacturing stage of PEMFCs used for FCEVs. The study shows that manufacturing stage contributes significantly to environmental impacts, e.g., acidification and GWP. The contribution analysis shows that platinum group metals (PGM) are major contributors to acidification due to emissions released during platinum extraction and processing. The flow field plates (FFP) also contribute significantly to environmental impacts, especially due to the electricity required for resin impregnation of the plates. The graphite used as conductive material in bipolar plates is highlighted as another main contributor to GHG emissions due to electricity demand for production [74].

Mori et al. present a component and material breakdown for PEMFCs. Materials with relative high cost are highlighted (e.g., PGM) as well as materials which are classified as critical materials such as perfluorosulfonicacid (PFSA) and sulfonated polyetheretherketone (s-PEEK) used in the electrolyte membranes or PTFE-Teflon used in the catalyst layer. The authors provide environmental impact indicator results for 1 g of material used in a PEMFC according to CML2001 methodology. The results indicate that platinum has the most significant environmental impact, followed by Nafion, PTFE, PEEK, and silicone [182].

Chen et al. present an LCA study of Toyota Mira based on breakdown of major components. The car is a hybrid vehicle with a drivetrain that combines a PEMFC and a Ni-MH battery. The battery supports the fuel cell drive during starting and acceleration. Inventory data for raw material acquisition, parts manufacturing and vehicle assembly are reported. The study assumes that the car is produced, used and recycled in China. With respect to the energy demand and the manufacturing of the key technologies, the fuel cell stack is most significantly followed by the electric motor, the hydrogen storage tank and Ni-MH battery [37].

7.2. Batteries

BEVs using LIBs are the most dominant EVs at the moment. LIBs contain a variety of materials [49]. Dai et al. discuss LCA results for NMC batteries (NMC111, prismatic cells, 143 kW/kg at the cell level, with N-Methyl-2-pyrrolidone (NMP) used as a solvent for cathode slurry preparation). When considering cradle-to-gate impacts, the key contributors to energy demand and GHG emissions are as follows: NMC111 powder (36.4 % of energy consumption, 39.1 % of GHG emissions), the cell production process (19.2 % of energy consumption, 19 % of GHG emissions), and aluminum (18.1 % of energy consumption, 17.0 % of GHG emissions). Additionally, the use of synthetic graphite and copper significantly increases environmental burdens. Within the cell production process, the dry room is the most energy-intensive component. Since NMP is used, electrode drying is also a critical factor, requiring heated air to maintain NMP vapor concentrations well below its flammability limit [46].

Regarding the use of NMP, Yuan et al. [299] present an LCA study in which they replace the NMP solvent and the polyvinylidene fluoride (PVDF) binder with an aqueous binder material and deionized water for the manufacturing of NMC batteries. The authors note that up to 38 % of the energy demand in cell production is attributed to drying processes and the evaporation and recovery of the NMP solvent. Their calculations indicate that water-based manufacturing processes can reduce energy demand in cell production by 43.2 %.

Within their study, Dai et al. [46] also highlight that the location of the battery production site as well as the sourcing of battery materials can significantly influence the LCA results. Supply chains for battery materials are dynamic and geographically distributed, which often leads to missing transparency regarding the origin of the material, the path from the mine to the product and the involved process technologies. However, these aspects influence the environmental footprint of materials [164], the LIB as well as the BEV in general [32,44,54]. The resulting geographical and technological variability leads to challenges for the data quality and impact results in the LCA, especially regarding the representativeness [58,134,164,215].

Several studies analyze the supply chains of primary raw materials based on available LCI data. Popien et al. [203] analyze the influence of different supply chains on the environmental impacts of different LIBs. Khakmardan et al. [134] analyze different supply chains for lithium carbonate in the battery production and the resulting environmental impacts. Engels et al. [57] conduct a similar analysis for different supply chains and available datasets for graphite production. In another work, Engels et al. [57] present an LCI for primary data for the production of natural graphite which is ranked as representative of the market.

Also, Manjong et al. [164] focus their work on models of the primary supply chains. They analyze the supply chains for several battery materials and identify the most relevant process parameters for each process step. Based on this analysis, they developed parametric models which allow for the evaluation of the supply chain considering the specific process technology and locations. The analysis of important process parameters also supports the LCE by identifying levers for process improvement. In a further work, they perform a comparative criticality assessment considering different cell types and criticality aspects to develop less critical value chains in the future. They identify for example cobalt-free cell chemistries as an LCE measure [163].

Another challenge is the scaling of data. While there are already established process technologies for all life cycle stages, rapid advances in technology development can be observed [72,142]. New material resources are discovered and therefore extraction and processing technologies are being developed. Production and recycling processes are further being developed [72,142] and new battery technologies are examined along with the question of which materials to recycle [139]. Therefore, processes operate at different technological readiness levels and production scales. For a comparability of established and emerging processes, the data for the LCI needs to be brought to the same scale [51,91].

Von Drachenfels et al. [52] suggest and implement a modularization approach combining different process models into a model of the process chain and the factory. This approach facilitates the reusability of available models and therefore also the assessment of new developed processes in the context of already existing process chains. This enables an early-on assessment of new processes and allows more LCE on the process before it reaches a large scale and a high technological readiness level.

Another approach is developing models based on simulations of processes. Thomitzek et al. [258] perform a simulation for the energy demand in the battery production. While this work focuses on the energy exclusively, other publications show the benefit of including material flows in the simulation as well [4]. In the battery cell production, the dry room needed for most of the process steps is responsible for a large share of the environmental impacts because of its high energy demand [52]. The environmental impacts in the cell production depend on the location of the facility since carbon-intensity of grid electricity varies as well as the ambient temperature and weather conditions influence the energy demand of the dry room [276].

7.3. Power electronics

Over the past decade, LCA-based approaches to understanding the manufacturing of power electronics has gained increasing attention due to their critical role in modern energy systems and associated environmental concerns. Nordelöf et al. [187] introduce a scalable model that determines the mass composition of a three-phase inverter equipped with insulated gate bipolar transistors, designed for controlling electric vehicle propulsion. Input parameters are nominal power, voltage, and cooling method (air vs. liquid). For an inverter with 110 kW, 300 V, liquid cooling the total mass is 12.5 kg with aluminum casing (49 %), DC-link capacitor (21 %), power module (13 %) and laminated bus bar (8 %) having the highest mass share. The developed model can be coupled with gate-to-gate manufacturing data allowing to compute LCI data. The data stems from literature, technical specifications, factory data, site visits, and expert interviews. The model covers various unit processes, e.g., electroplating, electro-galvanization, machining and anodizing, ceramic substrate fabrication. The author also explains how the model can be linked to the Ecoinvent database in order to calculate cradle-to-gate LCI datasets [187].

Brando et al. present LCA results for a three-phase inverter (150 kW, 450 V) with a total mass of 11 kg and based on a lifespan of 10,000 h. Focusing on the gate-to-gate-manufacturing and GWP the contribution of aluminum casing (57 %), power module (14 %), DC-link capacitor (12 %) and PCB (9 %) have the highest impact. Detailed breakdowns for the hotspot subcomponents of the inverter are provided. Taking the power module as an example, the results show that the copper baseplate, contacts (wire bonds, auxiliary terminals) and chips (IGBTs and diodes) are most relevant [16].

As power electronics are also in focus when it comes to end-of-life, good accessibility and greater weight encourage separation before further shredding of the remaining car. Bulach et al. [27] for example present a recycling route for power electronics modules from EVs, based on the treatment of waste electrical and electronic equipment (WEEE). The LCA results show high net credits for all calculated impact categories. Minke et al. [177] study the recycling of single-phase on-board chargers (Si- and GaN; 3.7 kW class). The authors break down the mass to the subcomponents and further down to material classes. A theoretical mass-based recycling rate is calculated with 27 % to 29 %.

7.4. Electric motors

An early study on LCA (based on embodied energy) of electric motors for EVs used in an urban environment was presented by Klocke et al. [136]. The considered components, along with their main materials and mass, are as follows: shaft (42CrMo; 17.2 kg), lamination stack (low-carbon steel; 46 kg), magnets (Nd-Fe-B alloy; 1 kg), insulation material (PVC foil; 0.173 kg), impregnation (polyepoxide; 0.0036 kg), winding wire (Cu; 5 kg), and housing (Al; 4.8 kg). The data for raw material extraction was obtained from databases, while the manufacturing stage was modelled based on ideal processes. Housing production via die-casting (energy-intensive) and shrink-fitting of the shaft into the rotor (requiring liquid nitrogen) were identified as hotspots in the manufacturing stage [136].

Nordelöf and colleagues present, on the one hand, a detailed model for deriving mass estimations for a specific electric motor design. On the other hand, they introduce a detailed LCI model for PMSM manufacturing. In addition to models for electrical steel production, die-casting of aluminum housings, and enameling of copper wire, data for the permanent magnet production chain (Nd(Dy)FeB) is provided [189,190]. Based on these works, Nordelöf et al. [188] perform an LCA of three different motor types: (1) PMSM with Nd(Dy)FeB magnets, (2) PMSM with SmCo magnets, and (3) SRM with ceramic Sr-ferrite magnets. The functional unit is defined based on performance parameters, such as a top speed of 145 km/h, as well as a lifetime of 200,000 km under the Worldwide Harmonized Light Vehicles Test Cycle (WLTC). Regarding the production stage, the manufacturing of the motor subcomponents and assembly is assumed to take place in Sweden (Scenario A) or the US (Scenario B), while magnet production is assumed to occur in China, followed by transportation to Sweden or the US. The GWP results for the production stage show only minor variations, with values of 1.8–2.0 g CO_2-eq./km for (1) and 1.7–1.9 g CO_2-eq./km for (2) and (3). The magnet production contributes approximately 0.32 g CO_2-eq./km for (1), 0.18 g CO_2-eq./km for (2), and 0.15 g CO_2-eq./km for (3). Within motor production, the main environmental hotspots are steel manufacturing, followed by aluminum production for the housing and copper production for the windings. Besides climate change impacts, the study also discusses results for carcinogenic and non-carcinogenic human toxicity.

Also for electric motors, approaches that foster a circular economy are of importance. Jin et al. focus their work on the circular economy of the magnets within the motors. Since these contain rare earth elements, they are subject to supply risks. Their LCA proves circular supply chains to be an important way to mitigate environmental impacts in the e-mobility. They included several impact categories as well to provide a robust assessment and identified the biggest contributors in each impact category [123].

7.5. Implications of product and production-specific trends on life cycle engineering

Sustainability in the manufacturing of charging systems, fuel cells, batteries, power electronics, and electric motors is essential for the transition to sustainable mobility with EVs. These technology fields face both shared and unique life cycle challenges, which result in cross-sectoral and technology-specific research areas in LCA and LCE.

A key research area is the substitution of materials with high environmental impact and/or criticality. If substitution is not feasible, the focus should be on minimizing material use while maximizing efficiency (yield) along the process chain. In fuel cells, this includes alternative materials for membranes and electrodes, such as non-PGM catalysts, as well as the sourcing and recycling of critical raw materials, like rare earth elements. In batteries, crucial materials include lithium, cobalt, and nickel, while in power electronics, research emphasizes silicon (Si), silicon carbide (SiC), and gallium nitride (GaN). In electric motors, one focus is also on reducing the dependency on rare earth elements.

Another major research area is manufacturing and process innovations, particularly for energy-intensive processes. In fuel cells, this involves for example optimizing the proton exchange membrane manufacturing process, while in batteries for instance, advancements are needed in dry coating, solvent-free processing, and recycling-integrated production. Additionally, batteries and power electronics require innovations to reduce the need for special environmental conditions, such as dry rooms for battery production and cleanroom operations for power electronics production. The aforementioned LCE trends provide a direct link to future research demand, which is examined in the next section.

8. Future research demand and conclusion

As the demand for climate-neutral mobility will increase in the coming years, the widespread introduction of EVs on the market is essential. This is connected to the challenges during the manufacturing of e-mobility components as mentioned in Section 2. Therefore, research in various domains is necessary:

- Compared to ICEVs, the infrastructure has to be considered as a part of the mobility system. Due to the high dependency of charging infrastructure, new technologies for an automated manufacturing of infrastructure components are needed, which will lead to more infrastructure nodes in short time, including a significant cost-reduction while at the same time enabling highest quality and productivity.
- Compared to ICEVs, the multi-physical functionality of the EV drivetrain components requires several new technological developments. Since the products partly consist of thin layers or filigree structures and are made of climate-sensitive and scratch-prone materials, special attention needs to be paid to the handling of the products. The handling of flexible components and their precise assembly is especially challenging across all e-mobility components, e.g., during the fuel cell assembly. Research on the handling of non-rigid components is therefore crucial.
- Multi-physical product properties require the establishment and optimization of further electro-physical, chemical and laser-based manufacturing processes in the context of EV manufacturing. The development of new surface treatment processes, forming processes and assembly processes is also essential.
- AI-based and data-driven methods are crucial due to the complexity of process parameters. In battery production and power electronics manufacturing, data-driven and AI-based approaches improve design and processes, while AI for laser welding and numerical methods for bending are key research areas in electric traction motors. These simulation models and Digital Twin approaches enable a higher level of productivity. However, in addition to applying simulation models, the more strategic integration of production engineering expertise - know-how derived from conventional manufacturing processes in particular – is critical for facilitating the successful transformation towards e-mobility. This targeted utilization of domain-specific know-how ensures that the transition is efficient and scalable, allowing for the seamless adaptation of established technologies to meet the requirements of e-mobility production systems.
- A hybrid process chain is when a set of operations with continuous material flows interface with a set of operations with discrete material flows. Such a hybrid process chain represents a new level of complexity in manufacturing. Hybrid process chains, e.g., battery manufacturing, have new research needs related to process planning and organization, development and optimization of production machines, and smart solutions to discretize the set of continuous operations at the start of the process chain.
- Moreover, production systems must be able to react quickly to new product variants as well as to new materials. In particular, scalability must be ensured, especially for the manufacturing of power supply, power electronics and the electric motor. In addition, flexible approaches must be developed, especially for the manufacturing of batteries. In that context, new production systems like agile production systems have to be established, which is connected to a high future research demand.
- One of the most important levers for the widespread introduction of e-mobility is cost reduction in the production of EVs, which goes hand in hand with the development of new manufacturing technologies, improved cycle times and a faster response to changing market scenarios. This results in another acute need for further research activities.

In addition to the aforementioned cross-domain future research needs for the widespread adoption of electric mobility, there exists a component-specific as well as an LCE-specific research demand, which is outlined in the following sections.

8.1. Power supply systems

As previously, 8.1.1 will first address future research demand in the research field of charging systems and 8.1.2 will then address the demand for fuel cells.

8.1.1. Static and dynamic charging

The automation of the assembly and wiring processes has a great impact on the future of the production of conductive stationary charging systems. As an enabler, consistent engineering and data flow will also play a major role. On the product side, energy storage by the charging system for short-term peak loads must also be considered, as various approaches of the flywheel technology show [59,279]. Thus, the concept will result in changes in the product structure as well as in production. Apart from hardware improvements, the vehicle-to-grid concept that includes bidirectional charging is mainly a software issue and does not have a great impact on hardware structure and production concepts [252].

Similar to conductive charging systems, bidirectional wireless power transmission (vehicle-to-grid) requires increased functional integration of standardized communication electronics, but has little impact on the basic design and thus the process chain for manufacturing IPT systems [196].

8.1.2. Fuel cell

The next step in fuel cell manufacturing is industrial scale in order to further reduce production costs. Therefore, research is necessary especially in the forming and joining process of the BPP, the CCM manufacturing as well as the MEA assembly. For the components with high material costs due to the use of platinum and carbon fibers as the MEA, a deeper understanding of the material-process-performance-interaction needs to be achieved to avoid either scrap or unnecessarily tight tolerances in manufacturing. In contrast, the costs of BPP mainly result from the manufacturing processes which require in-line quality control to detect defects in early stages of BPP manufacturing. By developing digital twins on product, production system, machines and process level, the production ramp-up can be replaced by a virtual process to reduce time, costs and scrap compared to traditional approaches based on trial and error.

From a systemic point of view, the demand on green hydrogen production is no longer neglectable to make the fuel cell technology commercially and politically competitive. Consequently, the development of a mature process chain for electrolysis manufacturing becomes evident. The establishment of a reliable infrastructure for the storage and transportation of green hydrogen should also be accelerated.

8.2. Batteries

Manufacturers face new challenges and opportunities as battery technology evolves with specific product requirements. A key focus is improving energy density for longer EV driving ranges. Advancements in materials, such as silicon-based anodes, and novel cell architectures like post-lithium batteries, show potential to enhance energy density [166].

High energy density requires high compaction rates, which introduce mechanical stress, leading to defects like foil embossing and wrinkles. Understanding material-process correlations can help reduce these defects [290]. However, these advancements also introduce manufacturing challenges, particularly in electrode processing, cell assembly, characterization techniques, and advanced quality control measures [304].

Additionally, differences in active materials between LIB and sodium-ion batteries (SIB) require adaptation in production processes, such as drying, due to varying layer thickness and capacity [135].

Solid-state batteries (SSBs), currently under development, offer higher energy densities while addressing safety concerns associated with liquid electrolytes [305], Solid electrolytes enable the integration of more stable and durable electrode materials, enhancing longevity and efficiency. However, SSBs require specialized handling tools for accurate positioning and damage-free handling [185,291].

A specific focus is on All-Solid-State Batteries (ASSB), which eliminate liquid components and promise higher energy density and safety. However, ASSBs are still in the laboratory stage, facing challenges such as interface resistance, scalability, and electrolyte stability [102].

As production processes evolve, research is exploring flexible and agile manufacturing systems. Fleischer et al. propose an agile battery production system that reduces costs compared to conventional production lines when producing varying formats [65,106]. Since battery cell production must take place in a dry room, studies investigate the use of micro-environments and material flow systems to reduce costs [104].

Another research area is battery recycling and second-life applications. Advanced disassembly processes are being developed to improve hazard analysis and automated condition monitoring for Li-ion battery disassembly [76]. Efficient disassembly strategies, automation, and safe handling of used batteries are essential for sustainable recycling.

8.3. Power electronics

As shown in Section 5, the power module is the core component of a power inverter, most research on processes in the scope of power electronics for EV is focused on the power module packaging processes and materials.

Since the substrate used in the power module serves as an electrical as well as thermal interface between the chip and the load terminals or heatsink, this component and its manufacturing is in the focus of current research as well [98,192].

In terms of modeling approaches, a significant research area is the simulation of the manufacturing processes themselves. Such simulations aim at enhancing the process parameter selection as well as evaluating the manufacturability of potential new power module designs. FE simulations to model the wire bond process [176] in combination with data-based simulation model refinement [267] could be used to delimit the viable process window and thereby reduce the number of prototyping iterations.

8.4. Electric motors

Research on manufacturing electric traction motors primarily focuses on core processes, with data-driven approaches being particularly important. As shown in Section 6, the implementation of data-driven approaches in the bending and contacting process is useful for optimized stator manufacturing.

The optimization of electric traction motors aims to reduce material use while increasing power and efficiency. The winding process is a key research focus, with wave winding (continuous hairpin winding) emerging as an alternative to hairpin technology. It avoids twisting and reduces welding steps by using a single continuous winding per phase [85]. In terms of round wire windings, the filling factor can be increased through the automated trickle winding process [231], as well as by compressing round copper wires or applying litz wires [87,230]. These technologies will not be able to compete with the fill factors of flat conductors and will tend to be limited to special applications. Furthermore, the forming of the wire to trapezoidal cross-sections for an increased mechanical fill factor is state of research [12]. In research some investigations on radially laminated stators [10] or flux barriers by simultaneous forming of multiple sheets [11] are in focus.

With focus on the rotor, innovative methods for automated assembly and fixation of permanent magnets that can be achieved by standard industrial equipment are examined [69]. Furthermore, lightweight concepts based on composites [138] and a segmentation of the rotor lamination stack are developed [154]. To reduce material costs, the replacement of the copper wires by aluminum wires is currently discussed, but the joining processes as well as the efficiency in operation are challenging [2].

8.5. Life cycle assessment and life cycle engineering

LCE is needed to support the development of production technology to make sure the development is aligned with overarching climate goals. As described in Section 7, the base of the LCE is the LCA. A significant gap that still needs to be filled is transparent and consistent modeling in the LCA of e-mobility. The LCA methodology leaves various decisions to the user. A harmonized approach in the modeling for all EV and their components is needed to ensure that developed models and collected data can be compared and combined. This gap needs to be filled for a meaningful LCE.

To foster an LCA-based engineering of production technologies and systems for electric mobility, it is essential to improve the understanding of material-process-structure-property relationships along process chains and integrate these insights into LCA and LCE models.

A key challenge in LCE for EV technologies is the variability of environmental impacts across the life cycle, depending on technological, temporal, and geographical factors. This variability affects data availability, quality, and representativeness, making accurate assessments and robust decisions difficult. Furthermore, modelling challenges, such as allocation for multifunctional processes and integration of circular supply chains, require new methodological approaches.

To address these challenges, related LCA/LCE research is increasingly focusing on process, factory, and supply chain modelling. Various approaches are being used, including: i) using primary data to enhance accuracy, ii) developing models based on physical calculations to improve transparency, iii) applying simulation-based modelling to increase flexibility and predictive capabilities. A combination of these approaches could foster to ensure comprehensive and representative assessments that support the sustainable development of EV technologies. A promising approach to addressing and managing variability in EV technologies is to support LCE with computational approaches [31,32]. In this context, the life cycle stages—from raw materials to end-of-life—as well as the background system are represented by models. Models are particularly valuable because they can capture variability in the life cycle stages in a better way compared to static data. To facilitate result interpretation, a visual and ideally interactive interface for accessing models is important [31,128]. Furthermore, LCE based on an absolute environmental sustainability assessment (ASEA) is an emerging research field for EV technologies and highly relevant [4,145]. One reason for this is that one of the core motivations for EVs is the reduction of environmental impacts associated with individual mobility. This means that if EVs become widely adopted globally, the environmental impacts linked to their production must be drastically reduced. Otherwise, in terms of absolute sustainability, not much will be achieved.

9. Conclusion

Production technologies and systems for e-mobility represent a highly interconnected system characterized by complex dependencies. To date, many of these dependencies are not yet fully understood, requiring the development of numerous processes and methods to enable an efficient and highly automated production. Given the volatile market demand and the dependency of various external factors, there is a need for ongoing research and development. This includes addressing the significant cost pressure on the production system, and finding a compromise between achieving quality and cost reduction. From today's perspective, the industry serves as the driving force behind innovations in e-mobility, advancing technologies and implementing practical solutions. Academia then builds on these developments, conducting detailed scientific analysis and evaluation to deepen understanding and uncover further optimization potential. In addition, the task of academia is to provide methods and models for enabling and optimizing production, whether through basic research or modeling for immature processes. Nevertheless, it remains to be proven that these approaches indeed contribute to enabling climate-neutral mobility in the future, necessitating additional development of assessment methodologies in the context of life cycle engineering.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Jürgen Fleischer: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Conceptualization. **Dariusz Ceglarek:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Jörg Franke:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Christoph Herrmann:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization.

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