FRAUNHOFER INSTITUTE FOR PRODUCTION TECHNOLOGY IPT

DISCUSSION PAPER

FUTURE ENERGY STORAGE SYSTEMS FOR MOBILITY APPLICATIONS

EXECUTIVE SUMMARY

A quick guide for the manufacturing industry as well as mechanical and plant engineering

The increasing demand for energy storage solutions presents a huge opportunity for mechanical and plant engineering as well as the manufacturing industry.

More and more OEMs are investing in the development and production of energy storage systems and electric drive trains. In order to facilitate the transition to zero emission energy consumption, further development of the technology and production of energy storage and conversion systems is required. The Fraunhofer Institute for Production Technology IPT, with its more than 35 years of experience in applied research and development of manufacturing technologies and processes, is committed to contribute significantly to this transition.

This study provides an insight into the most relevant energy storage technologies with regard to their principle of operation and design, their market potential and their manufacturing technology. On this basis, companies can make profitable decisions about new strategic alignment and investments.

The given technological options for energy storage are assessed regarding their suitability for the application to electrification of vehicles. Due to their general suitability for the application to electric vehicles, Lithium-Ion Batteries and Fuel Cells are selected for a detailed profit/loss consideration. This study shows that commercial vehicles like long-range buses and trucks, are means of transportation for which the Fuel Cell is a superior solution because of technical as well as economic aspects. The main hurdles for Fuel Cell market diffusion concerning these applications are currently high production costs and a TRL below 9.

Advancement of manufacturing technology and up-scaling are efficient means for cost reduction and thereby for achieving market distribution. An analysis of the production process, consisting of component manufacturing as well as assembly processes, is presented as a basis for technical development towards cost-efficient Fuel Cell applications. The Bipolar Plate and the Membrane Electrode Assembly are the main cost drivers and are thus the most important components to concentrate cost reduction efforts on.

Moreover, current challenges and potential levers for cost reduction alongside with further optimization potential are discussed. Here, the expertise of Fraunhofer IPT is placed in its proper relationship to these needs.

Finally, an outlook on a following, second Discussion Paper "The Relevance of Fuel Cells for Mobility Applications" is presented.

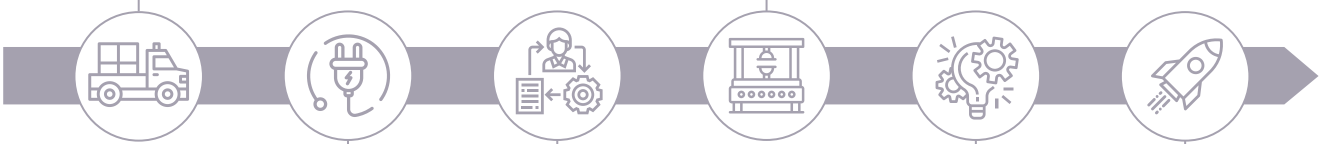
TABLE OF CONTENTS

CONTENT OVERVIEW

DISCUSSION PAPER I
FUTURE ENERGY STORAGE SYSTEMS FOR MOBILITY APPLICATIONS

DISCUSSION PAPER II (OUTLOOK)

THE RELEVANCE OF FUEL CELLS FOR MOBILITY APPLICATIONS



Potential Use Cases

Evaluation of a broad range of relevant **commercial vehicle use cases** regarding the most suitable option for FC-electrification.

Hydrogen Infrastructure

Analysis of the hydrogen infrastructure currently in place and **required for technology diffusion** in the future.

FC-System Requirements

Definition of technical requirements in order to guarantee the **technical suitability** of the FC for the use cases selected.

Technological Concept

Derivation of the **Fraunhofer IPT reference process** chain as well as **technological and production analysis of MEA and BPP** as the key components of an FC.

The Role of Fraunhofer IPT

Support of manufacturing companies through expertise in production technologies relevant for FC manufacturing as well as with **methodological and market knowledge**.

Conclusion

Successful manufacturing companies specify their **value proposition** according to a use case suitable for FC-electrification by developing and using **scalable production technologies and concepts**.

MOTIVATION AND INTRODUCTION

Electricity generation from renewable energy sources has continuously grown in the past few years and has reached a global capacity of over 2,300 MW in 2018 [INT19]. The variability of renewable energy such as wind or solar energy are in turn driving renewed interest in energy storage technologies.

The current trend towards renewable energy is driven by various factors. One substantial driver is the increased awareness of global warming. Worldwide, legal regulations to stop climate change are becoming ever more severe. International regulations have come into effect to cut greenhouse gas (GHG) emissions, which are known to have a significant impact on climate change. In pursuing ambitious GHG reduction targets, the European Union (EU) has agreed to reduce GHG emissions up to 40 % until 2030 – compared to a 1990-baseline. [EUR20] Various possible measures such as the implementation of a CO_2-tax have recently been discussed [ZAB19]. As the combustion of fossil fuels produces GHG emissions, the governmental regulations and measures directly affect fossil fuel consumers such as of internal combustion engine (ICE) vehicles and fossil-fuel based power plants [EHR18].

ICE vehicles are considered to be an essential lever for the reduction of GHG emissions. In addition to environmental damage by GHG emission, damage to health is caused by emission of pollutants such as nitrogen oxides (NO_X). As particularly urban regions suffer from ICE vehicle-related air and noise pollution, more and more cities are introducing driving bans for ICE vehicles. Furthermore, governments around the world not only discourage driving ICE vehicles through taxes and bans but at the same time promote the electrification of vehicles [BUN20, EHR18]. Furthermore, there is a rising public awareness of the negative ecological impact of ICEs. The concurrent trend in the mobility sector to electrical drivetrains is apparent in the continuously growing number of electric and plug-in hybrid vehicles. In 2018, an amount of 5 million cars worldwide was exceeded and the number of electric vehicles (EVs) has almost doubled in 2018 compared to the previous year [IEA19]. This demand for EVs is driving interest and investment in mobile energy storage technology development and manufacturing.

For a successful change to renewable energy, bridging the cost gap between electric and conventional solutions for stationary as well as mobile energy storage solutions and meeting the specific technical requirements of different applications is critical. To this end, industry and research centers need to make concerted efforts to systematically develop performant and scalable technology as well as production strategies. Along more and more OEMs that are investing in energy storage and electric drive train development and production, Fraunhofer IPT, with more than 35 years of experience in applied research and development in manufacturing technologies and processes, has committed to enhancing the development of energy storage and conversion system technology and production to facilitate the change to zero emission energy consumption.

The increasing demand for energy storage for applications such as shifting of energy from intermittent wind or solar power plants as well as for electric powertrains can be a huge opportunity for mechanical and plant engineering as well as manufacturing industry. In order for companies to be able to make an informed decision on new strategic alignment and investment, a profound examination of the various technological options for stationary as well as mobile energy storage is essential. This study provides insight into the most relevant storage technologies regarding their principle of operation and design. Thereby companies are enabled to better understand the technological capabilities of the energy storage systems and to evaluate their suitability for specific applications. To provide directors and managers with information required for farsighted and profitable strategic decisions, the market, and industrialization potential as well as the manufacturing technology for each energy storage solution are examined. Advantages and disadvantages, as well as potentials and challenges with a strong focus on production and manufacturing companies, are pointed out for all solutions. As EVs are considered an essential lever for the reduction of GHG emissions, alternative, non-stationary energy storage solutions for vehicles are focused. The most promising energy storage technology for application to EVs is determined. For the selected solution, a detailed examination and information for production development is provided.

ENERGY STORAGE SOLUTIONS

Batteries currently draw the most interest of all various technological options for stationary as well as mobile energy storage technologies. Especially Lithium-Ion Batteries (LIBs) are receiving public attention and are implemented in the first series of applications such as battery electric vehicles (BEVs). However, other storage technologies, namely Solid-State Batteries (SSBs), Supercapacitors (SCs), Flywheels (FWs) as well as Fuel Cells (FCs), must also be considered.

There are advantages and disadvantages over each solution as well as differences regarding their ability to fulfill technical requirements of the intended application, their technological maturity, market potential, and necessary production processes. A decision on the company's aptitude for the production of these technologies needs to include an evaluation of the necessity of research or machinery investments and profitability. This creates opportunities for production of the individual components as well as potential for machinery manufacturers. To facilitate such a decision, a brief summary of a profound internal study about the technology itself, advantages and current applications with a market estimation as well as an overview of components and production processes will be presented for each of these technological options.

Lithium-Ion Battery (LIB)

LIBs are electrochemical energy storage units, which are able to convert chemical energy into electrical energy. A major distinction of electrochemical energy storages is their possibility to be recharged. While so called primary cells can only be used once, secondary cells, such as the LIBs, can be recharged various times due to a reversible electrochemical reaction. Depending on the use and specific design of a battery, the lifespan can reach several thousand charging- and discharging cycles [RAH15].

Single LIB cells come in three different formats: cylindrical, prismatic and pouched cells. A LIB cell has two electrodes: the cathode, defined by reduction during the discharge phase, and the anode (see Fig. 1). LIBs vary according to materials used for the anode and the cathode. [GRE18] The cathode is lithium-based and the anode is traditionally constructed from carbon materials such as graphite. In between the electrodes you find a liquid ion-conducting electrolyte and a separator layer to isolate the electrodes. Both electrodes are coated to a current collector. [RAH15]

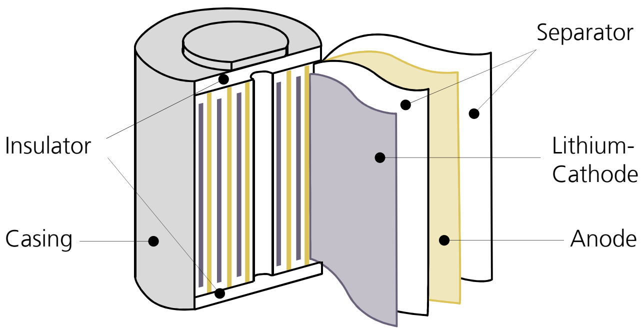


Fig: 1: Schematic Overview of a Cylindrical LIB Cell

To meet the required electrical performance of the consuming system, multiple cells are connected in series (increasing the voltage) or in parallel (increasing the maximal discharge current and the charge quantity). Connected cells are combined to form a module and multiple modules are again assembled to form a battery system, also known as a battery pack. The complete battery system includes these battery modules as well as electrical and mechanical components such as casing, insulation, cooling, fixtures, and the battery management system (BMS). [RAH15, HEI18c]

As for energy density, LIBs cover a relatively wide range of 160 to 670 Wh/l and 90 to 250 Wh/kg, respectively [RAH15, ISI17]. Amounts of up to 860 Wh/l or 320 Wh/kg, respectively, are anticipated for the future [RAH15, ISI17]. They can be charged at temperatures between 0 °C and 45 °C and discharged between -20 °C and 55 °C [HOP16].

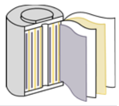
LIBs are used as power supply for portable electronic devices and electrical vehicles as well as backup and storage solutions for power grids. It is expected that global demands for these applications will continue to grow and that LIBs will stay the predominant technology for EVs in the future [SUM18, GRA17, LAR18].

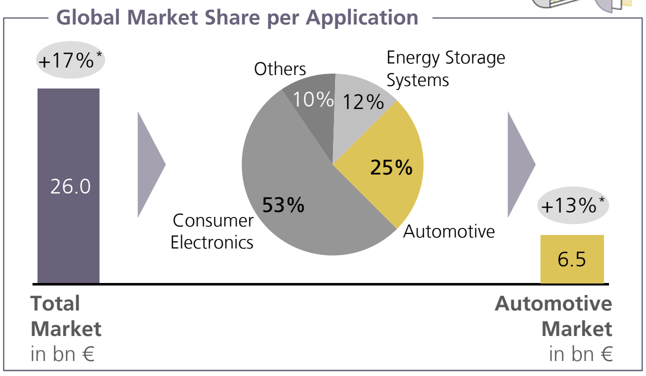
Global Market

LIB technology dominates the global battery market. As shown in Fig. 2, the current 26 billion EUR market for LIBs is expected to grow on average by 17 % a year between 2017 and 2025. Consumer electronics and automobile applications constitute more than three quarters of the overall estimated market, with a predominant increase in the automotive sector by 13 %. This development is largely due to the increasing demand in the mobility sector.

A strong commitment has been made by many OEMs towards this technology. Simultaneously, production limitations must be overcome. Strong demand for LIBs in Asia is taken care of by concentrated local production of companies like Automotive Energy Supply Corporation (AESC), a joint venture with participation of Nissan Motors (8.2 GWh), Panasonic (8 GWh), LG Chem (7.9 GWh), and Samsung SDI (5.6 GWh) [MIC16]. Considering the technology landscape, competitive SSBs could prevent larger investments through further enhancement of technology and scale-up of production of LIBs. It is therefore uncertain whether also the increased global demand can be matched by these key players.

Market Share and Growth





Market Drivers

- Inner-city driving regulations for conventional vehicles
- Increasing demand for e-mobility
- No "breakthrough" in potential competing technologies

Market Constraints

- Strong concentration of production capacities in Asia
- Uncertainty whether the production capacity can keep up with the rising demand
- Competitive SSB could prevent larger investments

*: Expected CAGR (till 2025)
Sources: [SUM18], [GRA17], [AHL19], [TRA19]

Fig. 2: Market Share and Growth of LIBs

Production Perspective

LIB-cell production requires electrode manufacturing, cell assembly and cell finishing. Additionally, the cells are assembled in modules and the modules are assembled into packs in a next step. The process chain concludes with flashing the battery pack and a quality check as outlined in Fig. 3.
The electrodes, anode and cathode are manufactured independently due to their different material but in the same way. Electrode manufacturing starts with the mixing of the electrode material and its application on a carrier foil. The coated

electrode material gets dried and compressed in a calendering process before the carrier foil, along with the electrode, is slit up into smaller stripes. Subsequently, the stripes are rolled up to small coils and vacuum dried. [HEI18a, BER17, PET13]

In the second major process step, these coils are unwound and cut into their final format for cell assembly. The single units are then either stacked or wound repeatedly with the separator layer. The resulting stack or coil is placed into a casing. Remaining cavities in the cell are filled up with the liquid electrolyte right before the casing is then sealed. [HEI18a, BER17].

The third and last major process step, the cell finishing, starts with the formation, a process of charging and discharging the cell with predefined parameters. During this process, the performance-critical solid electrolyte interface is formed. In the subsequent aging process, the cells are stored for up to three weeks with varying ambient temperatures. Throughout this time, the cell characteristics are measured to identify any faults in production. Finally, the main cell properties are measured for quality control. [HEI18a, GRE18]

Thereafter multiple cells are deposed and bonded inside a casing in order to form a module. For one battery pack, several modules and a cooling system are mounted together and assembled inside of a bigger casing. A final flashing process and quality check conclude the production process. [HEI18b, GRE18]

Technology Drivers, Constraints and Opportunities

LIB technology has a number of strong advantages such as its high energy efficiency. Furthermore, a strong commitment to this technology has been made by many OEMs. However, there are also challenging shortcomings with some of them being of systematic nature and currently unsolvable. For the application in EVs, these include a high weight-to-power-ratio, a limited cold start ability and a time-consuming recharging process. Nevertheless, high market growth is expected.

This high market potential creates an incentive for producing companies to enter the market, albeit with difficulties. The Technological Readiness Level (TRL) of LIBs is very high and the production largely industrialized. With large (and growing) battery cell manufacturing capacity especially located in China, significant efforts and investments are necessary in order

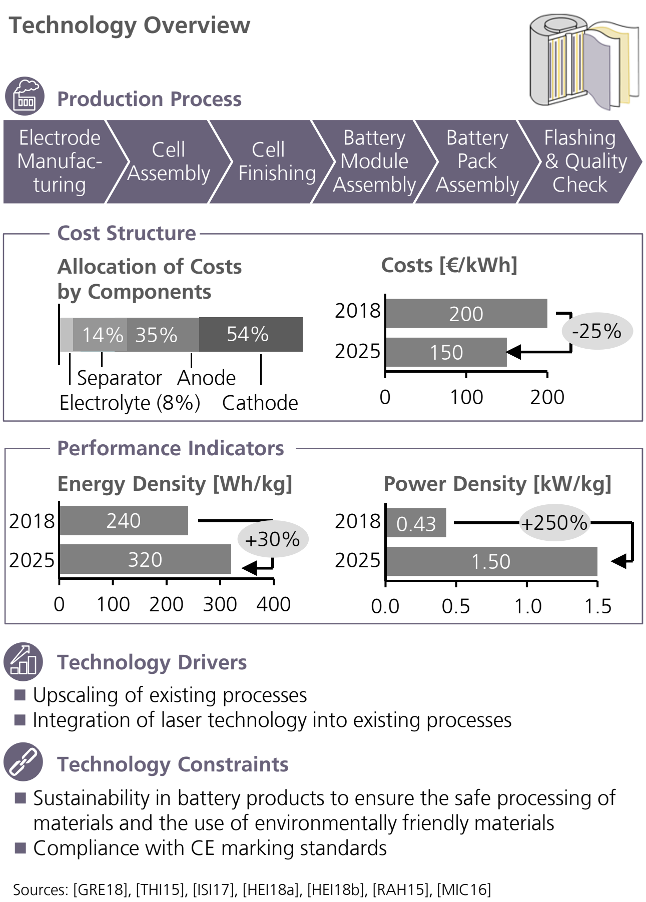


Fig. 3: Technology Overview of LIBs

to establish a competitive high-volume production facility [IEA19]. Additionally, approximately 60–66 % of the total manufacturing costs for a battery pack are material costs [WEN19]. Costs for the cathode material have the highest importance, followed by costs for the anode material and the separator layer. These costs largely depend on the battery chemistry and raw material costs. The high share of costs in material diminishes the potential to reduce costs by more efficient production. Further challenges for manufacturing companies include the use of sustainable materials, up-scaling of production, an increase of process stability, and facilitation of safe processes [RAH15]. The required know-how and effort to address these should not be underestimated.

An alternative to complete cell manufacturing is the specialization in sub-technologies. The processing industry plays a predominant role in LIB manufacturing while mechanical and plant engineering plays a subsidiary role. Skills in solid know-how in electrochemistry are essential to manufacture battery cells. Companies with the prerequisite competences need to be aware of the intense competition and overcapacity in electrolyte production [SAN17]. Other sub-technologies include extrusion and laser drying of electrode material, laser cutting of the electrode, continuous lamination of the separator layer as well as energy recuperation during the formation process. [HEI18a, HEI18c, MIC16]. This presents an opportunity for experienced mechanical and plant engineering companies to become specialized suppliers in these innovative sub-technologies. Cell and pack assembly is another sub-process that is potentially suited for market entry, as some car manufacturers have decided not to develop the required LIB pack manufacturing capacity in-house but to outsource it to specialist suppliers. GM, for example, has its cell and pack manufacturing activity completely outsourced. [LEB16] Additionally, fewer investments are required for module and pack assembly compared to cell manufacturing while profit margins are relatively high. From the point of view of market entry, a focus on sub-technologies such as module and pack assembly is therefore advisable.

Key Takeaways for the Manufacturing Industry

- High market growth is expected.
- Setting up a LIB cell production facility requires high investment levels and profound know-how in electro-chemistry.
- Process industry plays a predominant role in LIB manufacturing while mechanical and plant engineering plays a subsidiary role.
- Specialist suppliers for module and pack assembly need relatively low investments for market entry and can expect a high profit margin.

Solid-State Battery (SSB)

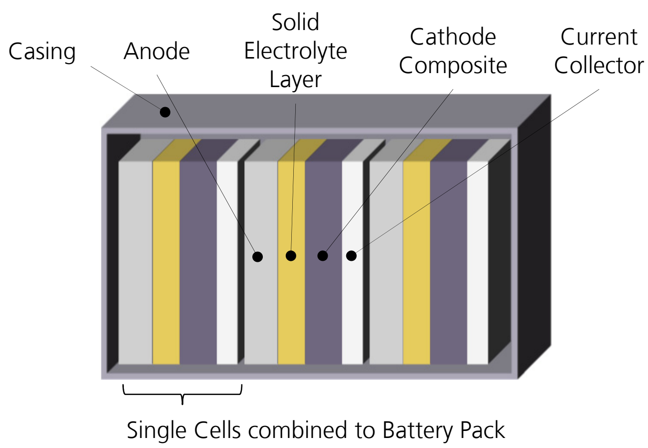


Fig. 4: Schematic Overview of a SSB

Like the conventional LIB, the main SSB cell is formed by an anode and a cathode layer, as well as the electrolyte (see Fig. 4). Both electrodes are layered on a current collector. The major difference to LIB cells lies in the intermediate electrolyte in between the electrode layers. Compared to LIBs with organic liquid electrolytes, SSBs are using a solid ionic conductive material. This solid material between anode, and cathode can be either a polymer electrolyte or an inorganic electrolyte. These materials are non-electric conductive and therefore also function as an insulator, which in LIBs is usually done by an additional component, the separator layer. [EEP18, HEI18b] Current research is focusing on anode, cathode and electrolyte materials. Polymer is one material option for electrolytes. Polymer electrolytes are easy to produce, have a flexible, shape and increase overall battery safety. However, they also have some significant disadvantages. These include a narrow operation temperature range, low mechanical stability, and an instable electrolyte/electrode interface. Another option is found in inorganic electrolytes, which can be classified into three categories: crystalline, glass, and ceramic. They are non-flammable and highly mechanically stable and therefore considered the best solution for safety issues. [EEP18]

Inorganic solid electrolytes allow for different anode materials compared to those used in conventional LIBs. The use of alkali-metals such as lithium metal, sodium or potassium facilitates a significant increase in energy density and cycle lifetime, a wider temperature range to operate in and shorter charging times. It is therefore seen as a huge technological advancement. Although cathode materials can be the same as in conventional LIBs, alternative cathode materials are possible for increased performance. The use of sulfur increases capacity whereas a higher voltage can be achieved by using lithium-nickel-manganese-oxide. [BRA16, HEI18b, SCH18]

The absence of a flammable electrolyte constitutes another advantage of SSBs compared to LIBs as it allows battery operation without a cooling system, freeing space for energy storage [SCH18]. In addition, the solid electrolyte enables new cell designs such as the bipolar stacked cells, meaning a cell stack in which the current collector, anode, electrolyte, and cathode are repeatedly layered over each other. The voltage can be tapped from the two outer current collectors. The more cells are stacked, the higher the voltage becomes. By using this design, the energy density can be increased because less inactive parts are needed. [GAM15]

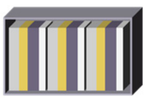
Possible applications are energy storage for portable electronic devices, power grids, and EVs [SCH18].

Global Market

The overall market for SSBs is comparatively small, with an approximate value of 110 million USD in 2018. The market is expected to grow up to over 2 billion USD in 2025, mainly due to the growing demand for thin film SSBs, which are used in small portable devices, and industrial applications. [GUP19] Despite this growth, the total market is projected to remain comparably small. EVs pose a particularly big opportunity, as automotive applications demand high energy densities, ideally above 800 Wh/l and 300 Wh/kg respectively, which current LIBs cannot deliver [SCH18]. Despite this growth, the total market is projected to still be comparably small. In order to have this technology diffused into the market the drawbacks consisting in high cost and lower performance at low temperatures need to be overcome.

There are a numerous key players that pursue a marketable SSB technology, for example research institutes like the MIT, ETH Zürich, University of Texas in Austin and Forschungszentrum Jülich [ELC17]. Next to the research institutes you find are a number of corporations and startups, which put a lot of effort into this technology. Based on the number of patents that are filed for SSB technology, at the beginning of 2019, key players are Toyota Motor Corp. (233 patents), Semiconductor Energy Laboratory Co. Ltd. (79 patents), Integrated Power Solutions Inc. (56 patents), Sakti3 Inc. (53 patents), or Robert Bosch GmbH (28 patents) [STR19]. Due to the investment by these players into research, the solution of cost and performance issues and therefore market diffusion seems likely in the near future.

Market Share and Growth



Market Drivers

- Electrification in the automotive sector (growing demand for PHEV and BEV with higher ranges)
- Miniaturization of end devices demands small energy storage solutions

Market Constraints

- Current development state restricts industrial use
- High costs due to small lot size and state of research
- Problematic heavy weights of batteries

Sources: [STR19], [MAR20], [SCH18]

Fig. 5: Market Share and Growth of SSBs

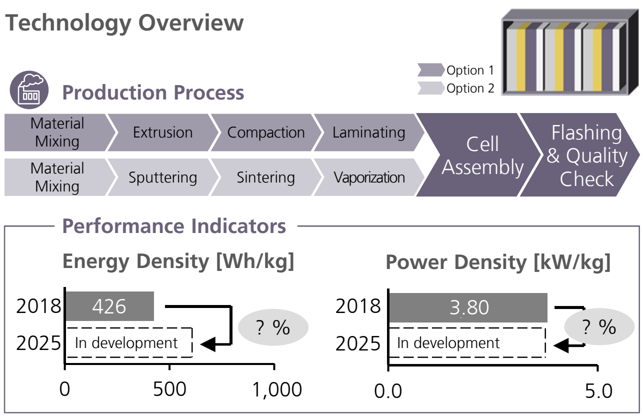
Production Perspective

The production of SSBs involves three main steps: electrode and electrolyte production, cell assembly, and cell finish. Due to the premature state of technology, there is currently no reference process chain for the production of SSBs. Specifically in electrode and electrolyte production, we find various sub-process chains that have to be further investigated on the basis of material developments. In cell assembly and cell finish, the sub-process chains are known and can be partially adapted from the industrialized production of LIBs. [SCH18, HEI18b] In the first of two sub-process chains of electrode and electrolyte production, cathode, and electrolyte materials are mixed in two separate compounding presses and then extruded with an extrusion tool to form a cathode-electrolyte composite. The lithium anode is produced in a single extrusion tool, and the required layer thickness is adjusted by roll compaction. In a laminating process, a layered composite of the cathode-electrolyte composite and the anode is produced using rolls [HEI18b, SCH18].

The second sub-process chain begins through mixing of the cathode and electrolyte materials in a ball mill and is followed by a high-frequency sputtering process. The cathode layer and then the electrolyte layer are applied. The layers are compacted using a sintering process and the resulting lithium anode layer is applied by thermal vaporization. [HEI18b, SCH18]

Cell assembly begins with the cutting of the primary cells using a laser, whereby contamination of the individual layers must be avoided. The elementary cells are then stacked bipolarly and applied with a compressive force for laminating the layers. Finally, the outer current conductors are made in contact and the stack is placed in an electrically insulated packaging [HEI18b].

The last process steps are flashing, testing the battery properties during aging, and conducting the final inspection with performance-specific clustering [HEI18b].



Technology Drivers

- Adaptation of industrialized production technologies from the LIB manufacturing with focus on electrodes-postprocessing
- Upscaling of existing process technically possible
- Material research promising

Technology Constraints

- Ionic conductivity and compatibility between solid electrolyte and anode have to be ensured by material selection
- Temperature instabilities and volume expansion during production of thin electrode layers

Sources: [THI15], [YAO16], [HEI18b], [SCH18]

Fig. 6: Technology Overview of SSBs

Technology Drivers, Constraints and Opportunities

SSB is currently characterized by a lower TRL compared to conventional batteries. Technological challenges include lithium dendrites, which grow on lithium metal anodes when the battery is charged or discharged. These dendrites can cause internal short circuits making the battery useless. Therefore the lower ionic conductivity of a solid electrolyte compared to a liquid organic electrolyte and the high surface resistance at the interface between electrolyte and electrode are immanent characteristics. [PRE17, HEI18b] Also production processes still pose a challenge and require further investigation. For instance, the production process must be adapted to the temperature instabilities and volume expansion of the materials. [HEI18b] An additional challenge in the production process that needs to be addressed, is the reactivity of the material, so that solutions which are suitable for series production must be developed taking into account health protection. [SCH18]

However, once the current material and production challenges are solved, serial production of SSBs can be expected. Based on the advantages outlined above, the SSB is considered the likely successor of the current LIB, provided that SSBs can be produced with the same quality as conventional batteries and at comparable costs. This means possible applications can form energy storage for portable electronic devices, power grids, and EVs [SCH18]. Due to low TRL and state of research, future performance indicators, such as energy and power density, are difficult to predict. Depending on the technology used, different energy densities can be obtained today or will be obtained in the near future. Recent research results, although not having been obtained under industrial conditions, give cause to optimism for future developments. [KIM19, IME19, YUS19, STR19]

The prospect of SSBs superseding LIBs is compelling and makes it worth to enter the market. In cell assembly and cell finish, the sub-process chains are known from LIB production and can be partially adapted from the industrialized production of LIBs. As the rest of the process steps cannot be transferred from LIB production, an opportunity for new players opens up as soon as the TRL is more advanced. Unlike LIBs comprising a liquid electrolyte, SSB manufacturing does not require a high share of competency of the conventional process industry but of several mechanical process steps such as high energy milling, heat treatment, and casting. Manufacturing of solid electrolytes for SSB is particularly attractive for companies that already have manufacturing equipment and knowledge of ceramics production (e.g. SOFC, LMCC), which can be adapted for ceramics-based SSB production [SCH19]. Currently, SSBs have a low TRL of 2.

Key Takeaways for the Manufacturing Industry

- Provided working in serial production, automotive OEMs are expected to use SSBs in BEVs as SSBs enable an increase of the driving range due to their targeted high energy densities.
- The share of mechanical value added in SSB production is higher than for LIB production.
- Market maturity is low and competing major players have not yet evolved, which creates an opportunity for a market entry of new players.

Supercapacitor (SC)

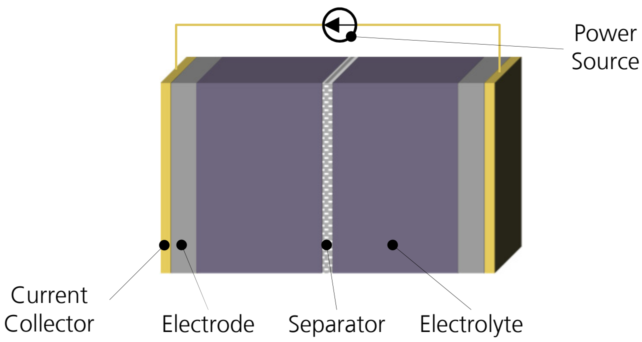


Fig. 7: Schematic Overview of a SC

Electrochemical capacitors use the capacitive properties of the solid-liquid interface between an electronically (electrode) and an ionically (electrolyte) conductive material for energy storage. As a further development of double-layer capacitors (EDLC), the SC consists of two electrodes, which are mechanically separated but ionically conducting with an electrolyte. [KUR15, YON16] When voltage is applied to the system, the positively or negatively charged surface is balanced by an accumulation of counter-ions from the solution. A double layer, the so-called Helmholtz-layer, is formed by these positive-negative charges [ENE18, YON16].

As shown in Fig. 7, SCs contain current collectors to connect electrodes with electrical inputs. Both collectors are coated with an electrode. These electrodes are isolated by a so-called separator, an ion-permeable membrane. An electrolyte connects both electrodes. The capacitor is either stacked or wound up in a rectangular or cylindrical casing.

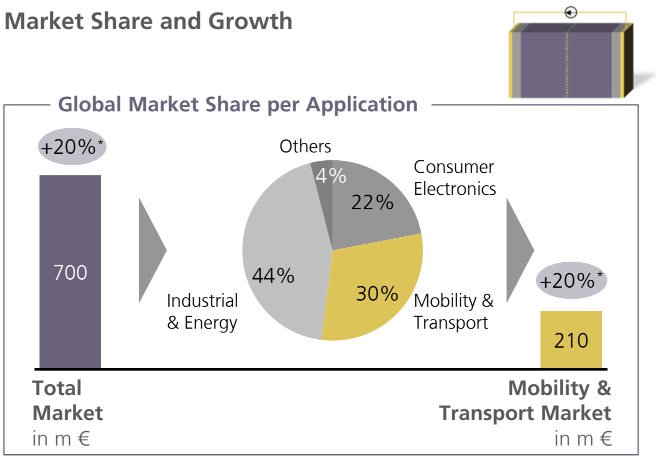
SCs are comparatively fast energy storage devices with access times in the order of seconds [GUE07]. The overall efficiency is as high as 98–100 % [KUR15]. The high power density and the ability of super-fast charging and discharging cycles make the technology attractive for applications which require a certain amount of energy in a relatively short time or a very high number of charging and discharging cycles.

Due to these properties, SCs are mainly used in the fields of industry and energy as well as for mobility and transport. Applications include their use in the power supply of light duty buses, locomotives, trams, cars, heavy duty trucks, material handling equipment as well as in auxiliary power units for off-road vehicles [INK17]. In these applications, they are used in particular as energy buffers to cover peak loads or for back-up power supply in case of shut down for short durations [GUE07]. Durations which can be buffered are below one second. Therefore, servo drives are potentially interesting applications. Further application examples can be found in energy storage in combination with intermittent generators and smart grids, mobile charging, sensors, or large-scale transport systems [MOR18, PAS17, GUE07, EPS16].

Global Market

In 2017, the global SC market was valued at around 700 million EUR and is expected to reach a compounded average annual growth rate (CAGR) of 20 % between 2018 and 2022 [MAT17, MAR16, FUT18, BUS18, IDT14, FIN18, MOR18] (see Fig. 8). Faster market growth of SCs is currently still delayed by scarcity in applications, unknown technological development potential and high prices [TRA18b, ALL17, DUR13].

Market Share and Growth



Market Drivers

- Transportation industry gives a significant boost to the market due to wider operation conditions in temperature, fast charging and regenerative braking
- Progress in energy harvesting applications, batteries, battery back-up and memory back-ups
- Increasing implementation in mobile applications
- Growing need to maintain high energy in energy industry, demand of high power densities

Market Constraints

- High price compared to conventional batteries
- Lack of awareness in technological application areas
- Technology is only used by a few companies in end devices, limiting the potential for high volume production

*: Expected CAGR (till 2022)
Sources: [ALL17], [BUS18], [BUS18], [ELE17], [EPS16], [FIN18], [FUT18], [FUT20], [GRÄ16a], [GON14], [MAR16a], [MAR16a], [MOR18], [PRN16], [TRA18b]

Fig. 8: Market Share and Growth of SCs

In comparison to other energy storage systems, SCs have unique features such as cyclicality and high power density. Due to potential usability in a wide temperature range, they are suitable for various applications. Moreover, the selection of different types and quantities of materials leads to significant variability in energy density, performance, and price [DUR13, YON16].

SCs are expected to solve existing boundaries with peak load demands due to their capability of fast charging and discharging, particularly in the market for renewable energy applications [GRÄ16]. Moreover, the usage in short-term storage applications, which are relying on high power density and low weight are strong incentives for a further technical development and market penetration of SCs [GRÄ16, PRN16]. These technical characteristics make SCs attractive for industrial and energy applications, resulting in a market share of 44 %. The second largest market share of 30 % is held by the field of mobility and transport. [BUS20, FUT18] Usage of SCs in EVs has advantages and disadvantages: They would allow for recharging wihtin a few minutes but limit the EVs to short travel distances. Another disadvantage of the technology is that a SC cannot store energy as long as LIBs – resulting in a loss of stored energy in case a car is not used for a longer period of time. Considering the present forms of use of EVs, the only utilization of SCs seems unrealistic. Only a combination with another energy storage system, e.g. a LIB, would allow for an application in EVs. [DEC18]

As today, important market participants are Maxwell Technologies Inc., Panasonic Corp., TOKIN Corp., Nippon Chemi-Con Corp., CAP-XX Ltd., and Skeleton Technologies [MOR18].

Production Perspective

The production process comprises six main process steps (Fig. 9) [HEI18b, ELN20, YON16].

Within the first step of cell assembly, the core components anode, separator foil, and cathode are wound or stacked. This process is characterized by high accuracy in positioning, cutting, and transporting is realized by a complex process monitoring. Additionally, special care must be taken in order to avoid electric charging. [YON16, ELN20]
After the cell assembly, the electrodes are equipped with electrical contacts. The electrodes are mostly put in contact by laser welding which provides high process speed and accuracy. Alternative technologies are ultrasonic welding, crimping, screwing, and resistance welding. The collector welding is followed by enclosing the cells in containers, during which density and in particular, fatigue strength must be guaranteed. [ELN20]

The following electrolyte filling is determined by the type of SC and whether liquid or solid electrolytes are used. While solid electrolytes are added already during the winding process, liquid electrolytes are injected into the cell via capillary action. After closing the cell with a laser welding process, a degassing-procedure by mandrel insert takes place. Precise dosage and taking into account the fire hazard are essential along this process. [ELN20, HEI18b] After closing the SC, formation, and aging is performed by charging and discharging the SC cyclically. This formation affects the cell performance and needs to be executed under stable conditions regarding the atmospheric environment. [HEI18b] Final tests complete the cell production process. In order to detect internal cell defects, cells are stored and checked over the course of several weeks.

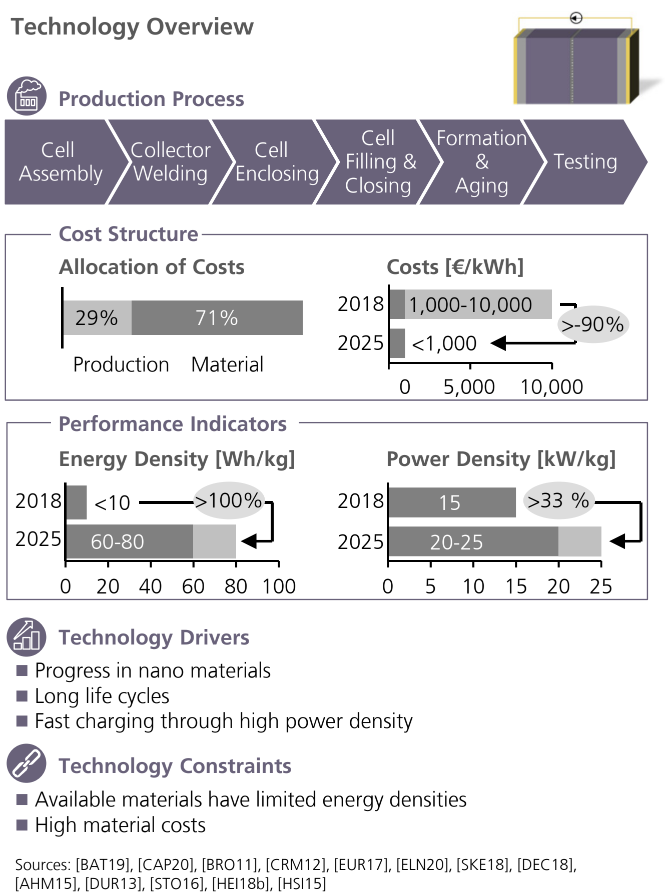


Fig. 9: Technology Overview of SCs

Technology Drivers, Constraints and Opportunities

Although the TRL is already high, in order to further establish the technology, optimization for lower material costs and higher energy density is important [FIN18]. With an improvement of the SCs relatively low energy density, the technology is highly dependent on a breakthrough in research of new capacitor materials. Optimization potential also exists in the integration of coating technologies for complex material processing. Furthermore, progress in nano-materials must be coupled with high accuracy in the production processes to ensure quality and performance of the SC [HEI18b]. Depending on the required cell format, synergies with LIB can be utilized regarding production steps. Especially the stacking processes is similar in both technologies.

As many of the manufacturing companies currently are emerging startups, the seller's market is expected to continue to change and develop [THO20]. With rising transportation industry demands the SC is able to give a significant boost due to broader operation conditions in temperature, fast charging, and regenerative braking [MOR18]. Therefore, there presumably still are opportunities to enter the market for new players in the material and coating industry.

Key Takeaways for the Manufacturing Industry

- SC market is currently not a mass market.
- Further research into new materials is required to improve energy density.
- Opportunities for market entry exist due to the currently high number of startups.
- Synergies with LIB can be used during production (electrode manufacturing, handling steps etc.).

Flywheel (FW)

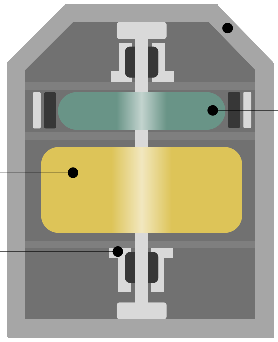


Fig. 10: Schematic Overview of a FW

In a FW system, energy is stored in form of kinetic energy of the rotating FW [STO20] (see Fig. 10). An electric motor is used to transform electric energy into FW kinetic energy and a generator to convert it back into electrical energy [WAN16]. When FWs are applied in vehicles for example, the kinetic energy can be directly stored without the need for conversion [THE11].

The most relevant component is the FW rotor, which is either made of fiber-reinforced plastics (FRP) or of steel. As FWs are mounted with bearings, energy losses due to friction occur during operation. In order to minimize air resistance of the FW, the chamber is usually evacuated [OER08]. Further components are the motor and generator unit, the bearings, the housing, and other components such as pumps and the control unit.

Characteristic for FW energy storage systems is its high power density, which allows for fast charging and discharging cycles [STO19]. Furthermore, they provide an outstanding life span with more than 100,000 full charging and discharging cycles, require only little maintenance and have a high efficiency [GRA19, PRN19, AKH15, KHO17]. Additionally, the performance degradation during a charging cycle is quite small [FRO18]. By using a magnetic instead of a mechanical bearing, the friction losses can be reduced to 5 % per hour [BUN16]. FRP-FWs are lighter than steel-based FWs but can produce a higher rotational speed and therefore can store a larger amount of energy [FRO15]. This is due to the quadratic dependency of the kinetic energy stored in a FW on the FW's velocity, compared to the linear dependency on the FW's mass. Another advantage of FRP rotors over steel rotors is the superior fracture behavior in case of damage [STE17].

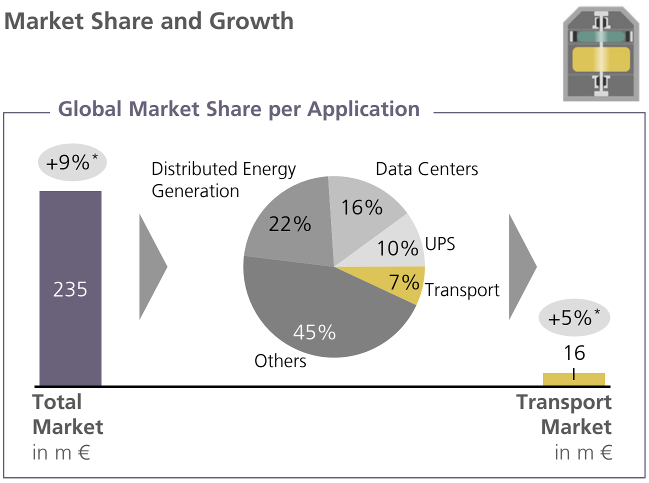
FWs can be used for stationary as well as mobile applications and are especially suitable for short-term storage of electrical energy [FRO18]. Stationary FWs are used for uninterrupted power supply, especially in data centers, storage to smooth out peaks in renewable energy supplies and smart grid energy storage [GRA19, ELY19]. In mobility applications, FW energy storage systems are mainly used for recuperation and power support of railways [MOU17]. Testing must show whether an application in other vehicles is realistic. However, an influence of the relatively large rotating mass on driving behavior of the vehicle cannot be excluded.

Global Market

By 2025, the FW energy storage system market of 235 million EUR is expected to grow with a CAGR of 8.9 % due to growing demand for uninterruptible power supply [GRA19]. The largest market share is held by distributed energy generation, followed by data centers. Complete market share distribution and market growth are shown in Fig. 11. The key players in the FW market are the German companies Gerotor GmbH, STORNETIC GmbH, Siemens AG, Piller Group GmbH, and other European companies such as OXTO Energy (UK) and ELYTT Energy (Spain). Moreover, American companies like Amber Kinetics Inc. and Beacon participate in the market.

With a rising demand for grid stabilization due to the increase of renewable energy, comes a growing demand for energy storage systems such as FWs. Their independence of rare resources gives FWs an advantage over chemical energy storage systems such as batteries.

Market Share and Growth



Market Drivers

- Long service life and efficiency
- Independence of rare resources
- Rising demand for grid stabilization as renewable energies expand

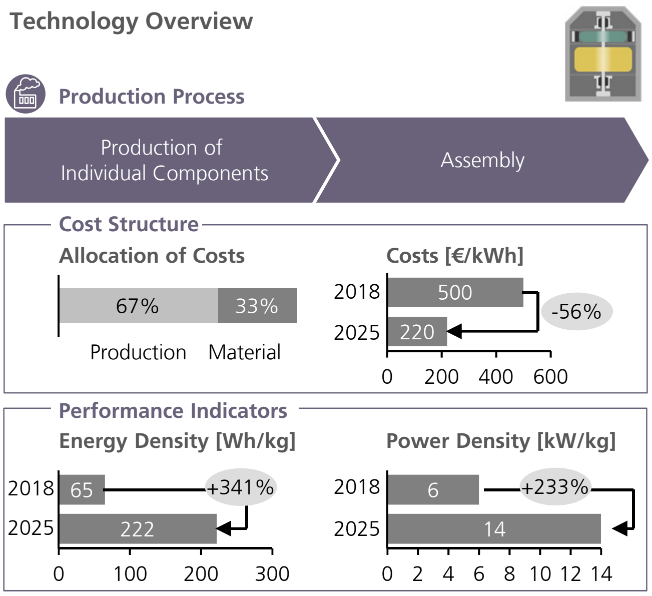
Market Constraints

- High cost
- Energy losses due to friction
- Limitation to short-term energy storage

*: Expected CAGR (till 2025)
Sources: [KH19], [GRA19], [INT17], [PRN19], [TRA18a]

Fig. 11: Market Share and Growth of FWs

Technology Overview



Technology Drivers

- Amount of stored energy can be increased by the use of FRP-FWs
- High life cycles
- Short term deployment of electrical energy

Technology Constraints

- Complex production process of FRP-FWs
- Additional technology required for vacuumed operation
- Estimation of lifetime is difficult for FRP

Sources: [BUC17], [INT17], [OER08], [PAS15], [TÄU17], [VEL20]

Fig. 12: Technology Overview of FWs

Production Perspective

The components are manufactured in discrete production. Most of the components namely steel rotor, bearings, motor and generator unit, housing, and pumps are well known mechanical parts, which can be manufactured in conventional processes. A steel FW is usually produced by casting and finished by machining.

The production process of a FRP-FW rotor is significantly more expensive than for steel rotors. FRP rotors usually consist of multiple rims with different diameters [KAL18]. A FRP rotor can be produced from a thermoset matrix material using the wet-winding process, where fibers are led through a resin bath and then wound around a rotating cylinder. A different approach is a rotor consisting of thermoplastic material. Here, a tape winding process is used. Pre-impregnated tapes are unwound onto the surface of a rotating cylinder. Afterwards, an energy source heats up the tapes in the area of the contact to the rotating part, where pressure is applied in order to achieve consolidation. Both methods require specific system technology and process knowledge.

Technological Drivers, Constraints and Opportunities

FW energy storage systems produce various favorable characteristics such as high power density, an outstanding lifespan, and high efficiency. Nonetheless, market size and growth are relatively small which can be attributed to the limitation for short-term energy storage applications [FRO18] and a presumably challenging integration into vehicles due to rotation of the FW's mass. Currently, a number of small- and large-scale manufacturers are already present in the market [GRA19].

Yet, market entry might still be interesting as a low investment would be necessary for mechanical engineering companies with expertise in machinery for limited production of these mostly classical mechanical components with a high TRL. This especially applies to manufacturers of bearings and winding components. On the contrary, there are hardly synergies for manufacturers of batteries or other energy storage systems.

Key Takeaways for the Manufacturing Industry

- Market entry is easy for mechanical engineering companies such as manufacturers of bearings and winding components.
- Production of rotors can be interesting for companies with a FRP manufacturing background.
- FW market and growth are relatively small.

Fuel Cell (FC)

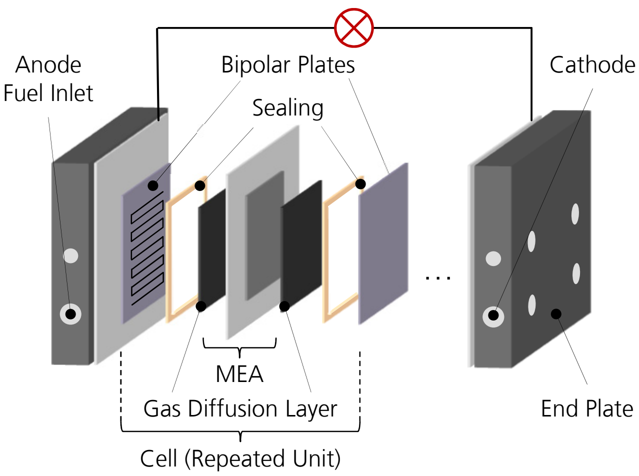


Fig. 13: Schematic Overview of a PEMFC Stack

A FC converts chemical energy of a fuel into electrical energy. The energy storage and converter system consists of the FC and balance of plant components (power electronics, thermal management, gas, and fuel processing system). In general FCs consist of two end plates and a series of connected cells in between. The structure of the stack and its components depend on the type of FC.

According to their operating temperature, FCs are divided into low-, medium-, and high-temperature FCs. Further distinction by the type of applied electrolyte is possible. Common FCs are the Alkaline Fuel Cell (AFC), the Direct Methanol Fuel Cell (DMFC), the Phosphoric Acid Fuel Cell (PAFC), the Molten Carbonate Fuel Cell (MCFC), the Solid Oxide Fuel Cell (SOFC), and the Proton Exchange Membrane Fuel Cell (PEMFC) [KUR16]. The way a FC system can be operated is characterized by its properties which vary between the different types of FCs: for FCs with low to medium operating temperature, the preheating time prior to operation can be shortened. Thereby, complex thermal management systems are avoided and a short start-up time is enabled. The high energy density of fuels such as hydrogen or methanol leads to a low system weight.

As an example for low temperature FCs, we show in Fig. 13 the structure of the PEMFC. A single cell is composed of a Bipolar Plate (BPP), the gasket, Gas Diffusion Layers (GDLs) and the Membrane Electrode Assembly (MEA). The MEA is built of two electrodes, each coated with a catalyst, and a polymer electrolyte membrane (PEM) in the center of the cell. [JÖR17]

Hydrogen-based mobility supports sector coupling, in which peaks from green electricity generation can be stored in form of chemical energy. At times of high demand, hydrogen can be converted back into electrical energy by FCs. In recent years, automotive manufacturers and suppliers are increasingly considering FCs as a possible technology to drive EVs. Three major technical requirements shape the application for transportation: short start-up time (low operating temperature), high efficiency, and low weight, which corresponds to high

FC Type	Operating Temperature [°C]	Electrical Efficiency [%]	Power Density [mW/cm²]
AFC	<100	60	100-200
DMFC	50-120	20-30	240
PEMFC	80-120	60	350
PAFC	150-200	40	200
MCFC	600-700	50	100
SOFC	500-1,000	60	240

Sources: [USD15], [FCT16], [RAM15], [FUE12], [PRA16], [PEI10], [LOU17], [STRE17], [KUR16]

Fig. 14: Key Properties of the Ideal System and Various FCs for Transportation Applications

power density [WEE07, WAN11]. Fig. 14 gives an overview of the technical suitability of different FC types on these demands. MCFCs and SOFCs require high operating temperatures and DMFCs have low electrical efficiency at their current development state. For AFCs and PAFCs, the power density is currently not competitive with densities of other energy storage systems. On the other hand, the operating temperature of PEMFC is between 80 °C and 120 °C (relatively low) with an electrical efficiency ranging around 60 % [JOU17, KUR16]. With their ability for discontinuous operation, PEMFCs are the most appropriate type of FC for the application to transportation and mobility. [USD15, PRA16, PEI10, STR17]

The PEMFC can be designed according to different technical requirements like output power or geometrical size to adapt to varying applications. This enables the use of FCs as a solution for zero emission mobility for both passenger cars as well as trucks and buses. Provided that hydrogen tanks are of the appropriate size, FC Electric Vehicles (FCEV) allow for high driving ranges and short refueling durations of only a few minutes. Fig. 13 shows a PEMFC stack where several single cells are connected in series [STE17]. With an increased number of connected cells, the FC can cover a high power demand and can be deployed in a wide range of geometrical sizes [JOU17]. The focus of this study is on the PEMFC due

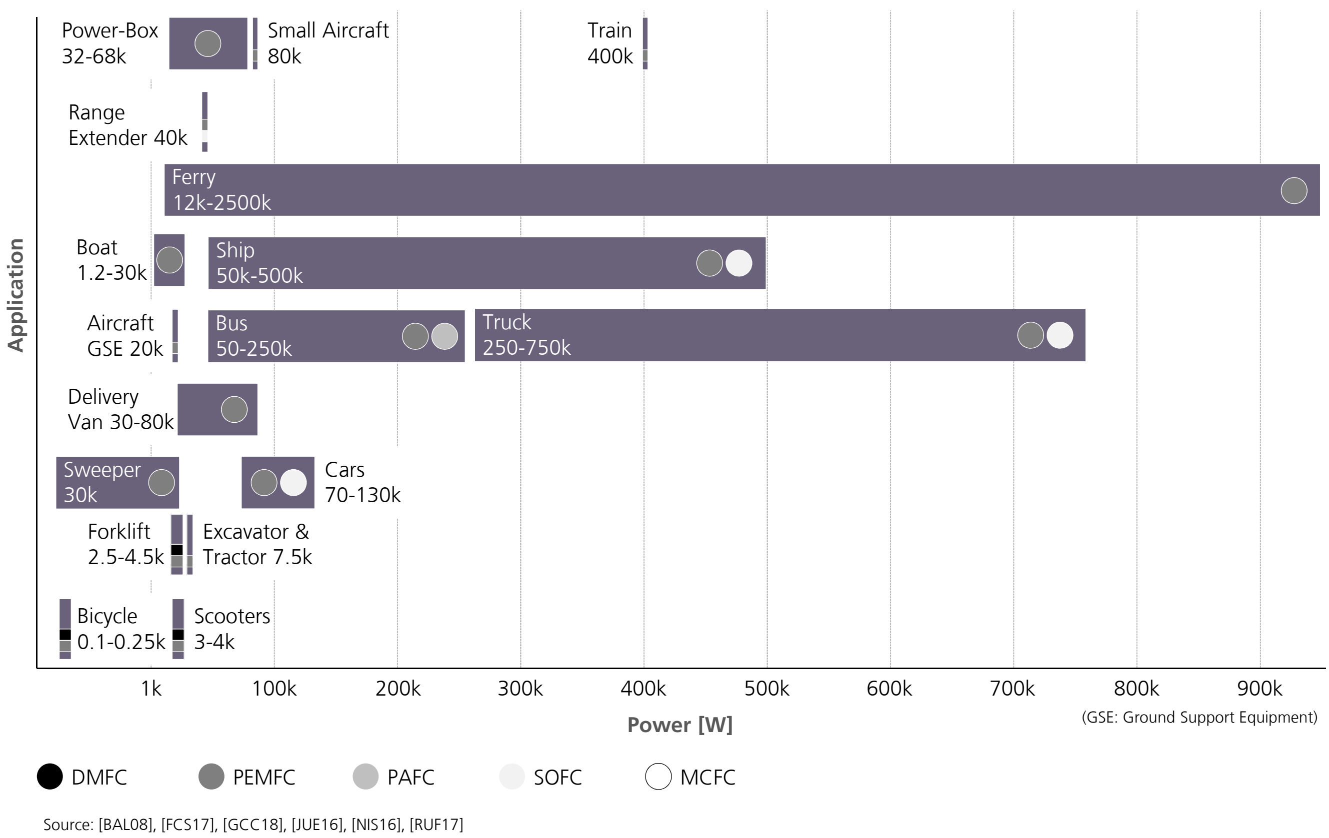


Fig. 15: Overview of Industrial Applications for Different FC Types

to these properties and the special suitability with regard to operating temperature, electrical efficiency, and power density as described above.

PEMFCs convert hydrogen and oxygen into electrical energy, water, and heat [VIE17]. Inside the cell, hydrogen is separated into electrons and protons at the anode, where a catalyst is applied. Anode and cathode are separated by a PEM which enables the transfer of the protons but is impermeable for electrons. At the cathode, electrons, protons, and oxygen are processed to pure water. Electrons are transferred from anode to cathode along an external circuit, which is used to extract electrical energy from the cell. [PIT17]

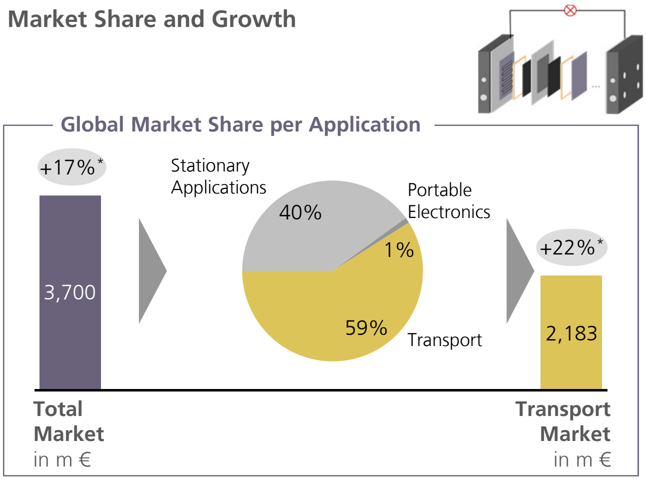
Fig. 15 shows various possible applications of FCs including concept and research projects in the transportation sector. The purple illustrate the required power ranges and small circles indicate currently used types of FCs. As shown in the figure, the PEMFC is used in every application making it the dominant type of FC for mobility applications [RUF17]. Next to the application in the transportation and mobility sector, PEMFCs are used for uninterruptible power supply [JÖR17], portable electronics [CUR17], onboard systems for submarines and airplanes [KUR16], and stationary applications like combined heat and power generation [JÖR17, CUR17].

Nevertheless, other FC types have been used in selected cases. SOFCs can be found in mid-range power applications such as cars, trucks, and ships [NIS16, REC16, GCC18a]. Due to their limited maximum power, DMFCs are restricted to applications with relatively low power requirements such as bicycles, scooters, and forklifts [FCB08, FCS17]. Only one case of PAFCs was reported for commercial vehicles. No usage of AFCs and MCFCs was reported at all [USD03].

Global Market

As the global market for EVs increases also the number of FCEVs will rise. This will presumably influence the market of PEMFCs, which is therefore expected to grow by 17 % a year between 2017 and 2026 as shown in Fig. 16. Next to the large range and short refueling time, further advantages of using a FC in mobility applications are the low noise impact and the absence of pollutant emissions [GRA20].

Market Share and Growth



Market Drivers

- Large number of hydrogen-powered vehicles could enable sector coupling
- Extended range and uptime as well as shorter refueling time compared to existing energy storage options for EVs
- Growing market for electrical vehicles with high power demand

Market Constraints

- High costs compared to fossil energy
- Lack of hydrogen-infrastructure (difficult to create, store and transport)
- High demand for cost intensive materials like platinum

*: Expected CAGR (till 2026)
Sources: [HFC17], [INK17], [KUR16], [PRN19], [CUR17], [WIE19]

Fig. 16: Market Share and Growth of PEMFCs

The key players in the FC market working on these topics and the FC itself are Ballard Power Systems, Hydrogenics Corporation (both Canada), Intelligent Energy Ltd., Acal Energy Ltd. (both UK), Proton Motor Fuel Cell GmbH (Germany), Plug Power (USA), and PowerCell (Sweden).

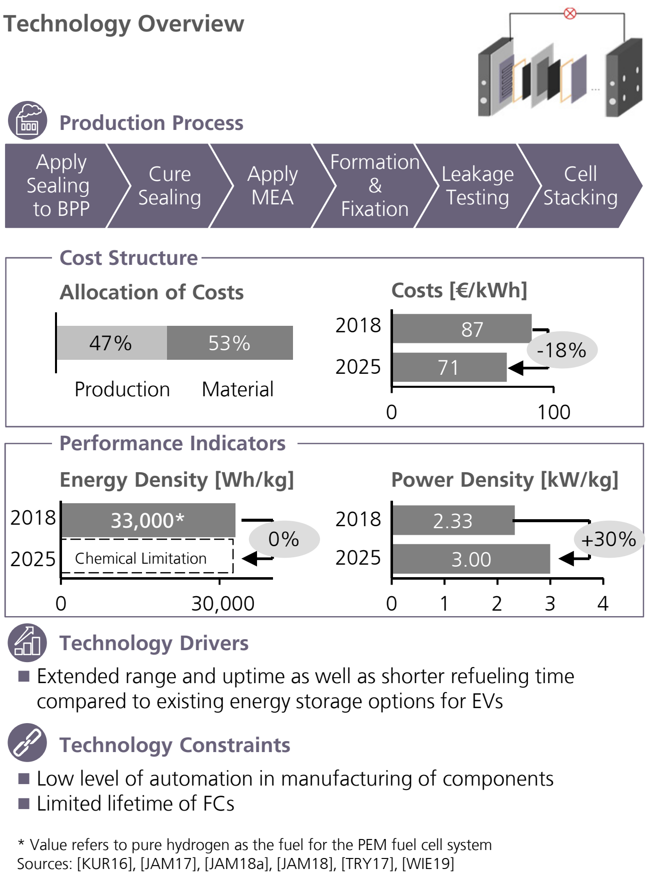


Fig. 17: Technology Overview of PEMFCs

Production Perspective

Components are manufactured separately, then assembled into cells and afterwards stacked . The assembly and stacking process of a PEMFC is composed of the six steps shown in Fig. 17, which might vary in detail. One possible process chain is described hereafter.

In the beginning of the assembly process, a chemically resistant gasket is applied to the BPPs in order to prevent internal and external leaking. Following this step, the gasket is cured in a continuous furnace. For a subsequent application of the MEA, the catalyst is placed upon the GDL or membrane and the layers are joined using hot pressing. With the following positioning of the BPPs and their connection to the MEA, a single cell is formed and then tested for leaks. In the last step multiple cells are lined up in a row and connected to a FC stack. [BAT16, BEN10, BLO05, CAR14, KUR16, JAM17, SCH05, ZBT12, ZBT19]

Drivers, Constraints and Opportunities

The hydrogen and FC markets are driven by increasing energy demand. However, LIBs are a competing solution, which is already available on the market and more widely used. They have a number of disadvantages compared to FCs and hydrogen tanks such as lower energy density and longer refuelling times, which are especially critical in the case of vehicles. To be an overall favorable solution compared to LIBs, PEMFCs still need to overcome a number of obstacles, namely high cost, short lifetime, and a lack of infrastructure. More precisely, the costs for the FC drivetrain need to be lowered to a price comparable to combustion or BEVs. Additionally, production processes need to be developed to achieve a long lifetime, which is currently limited for some of the components and for applications in the mobility sector and the infrastructure for hydrogen supply needs to be enhanced.

Growing demand for FCs accelerates the developments for a cost-optimized production [JAM18, ENE19]. The high costs of the current production process are mainly due to a high amount of manual processing steps as well as the high cost of certain materials. Especially an improvement of the BPP production will be a decisive lever for a considerable cost reduction. The costs for BPPs can be reduced by automation using technologies like hydroforming or stamping as well as advanced handling systems and process control. Therefore, BPP manufacturing requires a high level of competencies of classical mechanical engineering industry. The production of metal BPPs is challenging due to the necessity to form very complex flow fields and requires know-how about possible technologies and the corresponding processes. As there is the opportunity to be the first to develop and establish an automated flow production process, which enables high volume production at low cost, market entry is interesting for companies with experience in these manufacturing processes. However, it should be also considered that this requires high initial investment.

Besides BPP production, the cost-intensive MEA production needs to be improved. Here, the reduction of the amount of platinum, coated onto the MEA as catalyst, is the main lever [JOU17]. While BBPs are especially interesting for classical mechanical engineering companies, competency in chemicals is needed for catalyst production.

Besides component manufacturing, assembly, cleaning, and inspection bear opportunities for market entry for specialized companies with existing know-how.

Key Takeaways for the Manufacturing Industry

- Low-cost high-volume production is required.
- High investment for scale-up is required, but scalable production can tap cost potentials.
- BPP manufacturing, assembly, cleaning, and inspection are opportunities for market entry for specialized mechanical engineering companies.

TECHNOLOGY SELECTION

Preselection

A detailed analysis and comparison of the different energy storage systems with their advantages and disadvantages as well as the current market shares and potential growth fields provide a profound basis for a differentiated analysis.
For the application to electrification of vehicles, the above mentioned technological options for energy storage are not equally well suited (see Fig. 18).

SSBs are assessed as currently not eligible due to their lack of technological maturity. FWs and SCs do not offer sufficient energy storage capacity to meet the requirements of an EV. Hence, we project that they will not play a big role in the electrification of the mobility sector. On the other hand, LIB and FC technology are promising solutions for the electrification of vehicles.

With its high energy efficiency, LIBs are an attractive technology option offering a high level of technical maturity and are particularly suitable for small cars and rather short trips [FRI19].

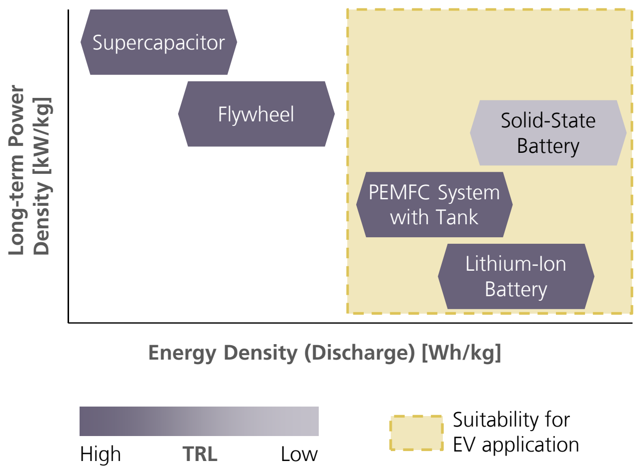


Fig. 18: Preselection of Energy Storage Solutions for Application in EVs

Certainly, limited capacity and range still are challenges for LIBs but the relatively wide developed recharging network already offers a great advantage for further development. Nevertheless, the technology is not suitable for every use case because of undisputed systemically and indissoluble disadvantages, which can be better covered by other energy storage systems.

In FCEVs, the FC produces electric energy from compressed hydrogen stored in a tank to power the electrical motor. Storing hydrogen in tanks leads to a very high-density storage solution, a low specific weight, allows for a higher range and faster charging times. However, high production costs as well as a not yet sufficiently established hydrogen infrastructure for production, distribution, and storage hinder technology diffusion. [HYD20]

Due to their general suitability for the application to EVs, we have selected LIBs and FCs for a further consideration.

Usability for Different Types of Vehicles

The electrification of vehicles is suitable for a variety of means of transport. As illustrated in Fig. 19, the degree of suitability of BEVs, (FCEVs) and synthetic fuel powered vehicles for the different applications depend foremost on carried weight and average mileage per day or trip [HYD20].

Key industries have committed to LIB technology. However, a closer look reveals, that battery technology bears a number of disadvantages.

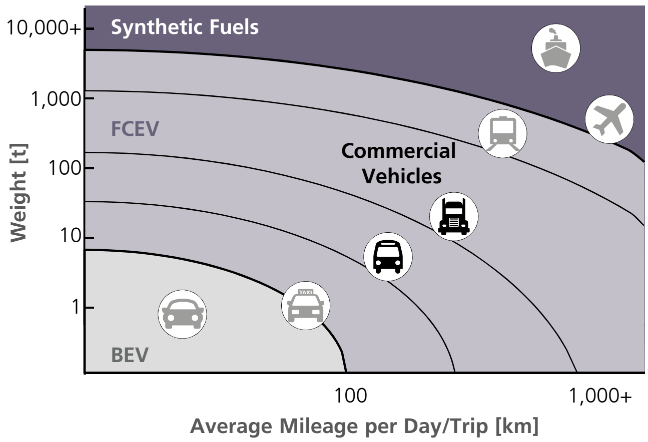
The weight and size are proportional to the amount of stored energy. Thus, for long-range applications, the necessary high weight and size of the LIB increase any energy consumption and reduce the freight capacity. This effect amplifies with an increasing target range. [DVZ18] When the range supported by the installed battery is exceeded, long vehicle downtimes due to slow charging occur. Additionally, for long distance trips (>430 km), GHG emissions of BEVs even surpass those of alternative powertrain solutions when electricity or hydrogen is produced with natural gas [THO09, HYD19].

On the contrary, FC technology enables refueling within only a few minutes. Furthermore, an increase in range is achieved by an enlargement of the hydrogen tank and does not imply a significant weight increase. Despite their current technological delay compared to LIBs, the advantages here exceed the disadvantages. All in all, high battery weight, capacity, and charging time, are particularly negative elements for long-range and heavy duty vehicles. [THO09, HYD17] Therefore, commercial vehicles like long-range buses and trucks are use cases for which the FC is the superior technological solution – either in the form of a dynamically configured FC (direct reaction to increased power demand) or in the form of a range extender that buffers power peaks via a LIB (see Fig. 19) [FRI19].

Comparison of Costs for BEVs and FCEVs

Competitiveness regarding the investment costs is crucial in this cost-sensitive sector, and cost-considerations will complete the comparison of BEVs and FCEVs. In order to obtain a valid estimate, it is necessary to ponder the use cases like passenger cars and commercial vehicles individually due to their tremendous differences in initial and operating costs, driving profiles or weight. Fig. 20 and Fig. 21 show the dependency of investment costs (CAPEX) from the required driving range for FC electric as well as battery electric passenger cars and commercial vehicles, respectively. The shown curves are based on market data.

BEV show an over-proportional dependency of investment cost from the driving range. The nonlinear behavior of the BEV investment cost function is a result of the gravimetric energy density of LIB packs. The significant extra weight of the



Source: [HYD17]

Fig. 19: Energy Storage Technologies for Different Transportation Use Cases

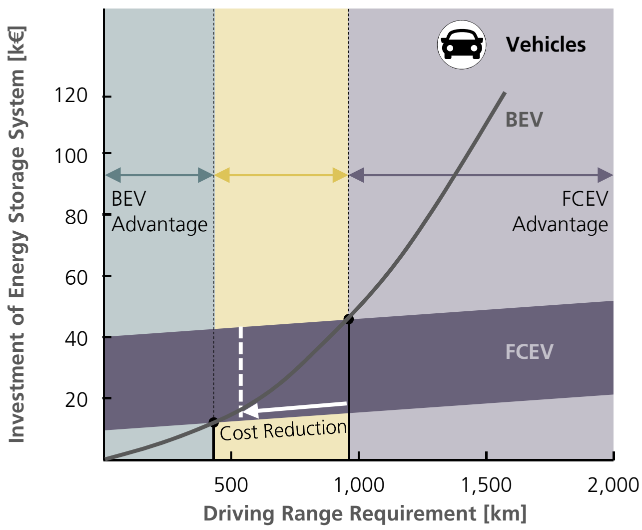


Fig. 20: Comparison of Costs for BEVs and FCEVs over Required Range for Passenger Cars

battery increases the vehicle energy consumption and thereby causes an over-proportionally heavier LIB that must provide the energy needed for a certain driving range. It has to be noted, that the dependence of LIB range investment costs differs for different vehicle energy consumptions. According to this case, the vehicle energy consumption depends on the vehicle specification and may lead to a curve shifting.

Investment costs of the FCEV comprise FC stack costs of 10,000 EUR to 40,000 EUR on top of the cost for the hydrogen tank. This combination is comparable to the function of a LIB in a BEV. Lifetime expectancy is not taken into account. It has to be noted that FC stack costs are currently highly uncertain as they will likely be lowered through upscaling of production (see Fig. 20) and reduced material consumption and costs in the future. Thus, instead of a curve, a range for the investment costs is defined. In contrast to the investment costs of BEVs, those of FCEVs increase linearly with longer driving ranges. Considering the previous deduction, a longer driving range for the FCEV can be achieved by extending the hydrogen tanks while leaving the FC stack unchanged. The costs are therefore only rising slightly with increased driving ranges due to a slight increase of costs for the tank. The size and therewith the manufacturing costs of the tank depend on the amount of hydrogen that needs to be stored and its pressure level.

Due to the highly variable initial costs of FCEVs, an intersection area with LIBs exists in which a clear economic superiority of one over another cannot be determined. The positive range for BEVs is left of the intersection and for FCEVs right, respectively. FCs thus have a price advantage for long driving ranges.

For passenger vehicles, the driving range in which BEVs are advantageous is relatively wide (see Fig. 20). For commercial vehicles, the initial costs for FCEVs are higher compared to passenger vehicles, due to the higher power demand for its operation. However, BEV costs are rising rapidly as the

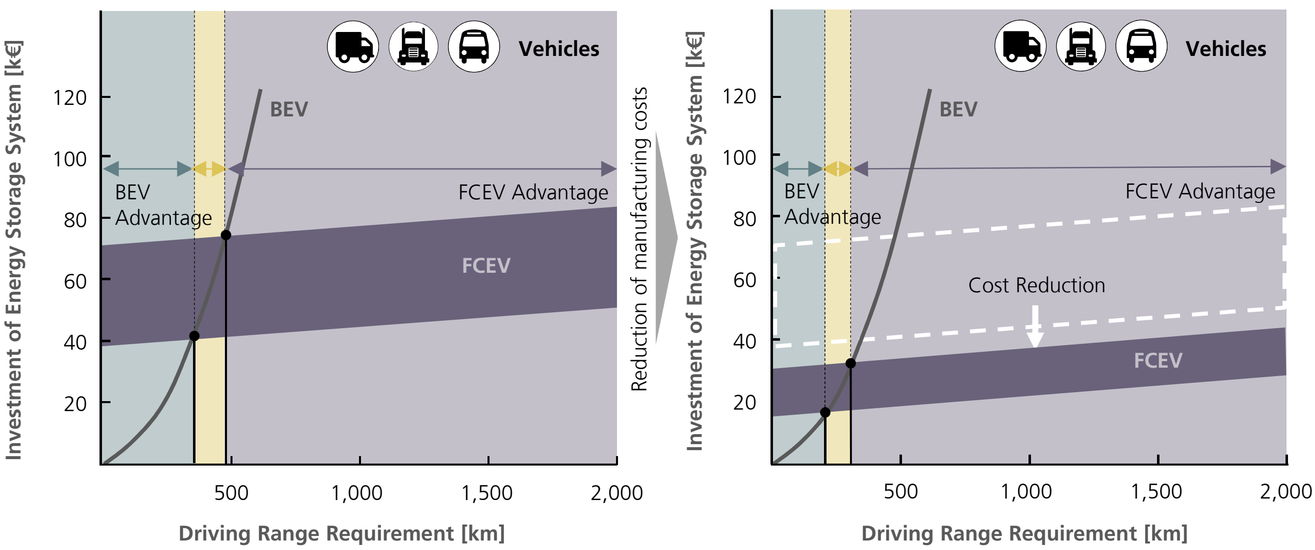


Fig. 21: Comparison of Investment Costs for BEVs and FCEVs over Required Range for Commercial Vehicles

driving range increases (see Fig. 21). As stated above, this is a consequence of the larger amount of energy needed due to a larger vehicle mass and the fact that heavier LIBs add to this vehicle weight. The figure shows that the driving range in which FCEVs are more advantageous is wider for trucks and buses than for passenger vehicles.

Cost reductions of FCs can be attained by production up-scaling, reduction of material costs, or manufacturing process optimization. The same does not apply to LIB production, which is already widely explored and optimized, reaching maturity with fewer levers for future cost reductions. The exploitation of this high potential for FC cost reduction leads to a shift of the intersection area to the left (see Fig. 21). This creates an attractiveness of FCEVs for an even wider area. This potential of FCs for future expansion to short-distance applications depends on the ability to push costs to this competitive level [CON11].

TRL of PEMFC

Aside the current lack of cost competitiveness, the main obstacle to a more intensive use of FC technology in commercial vehicles is the lack of complete technical maturity.

The TRLs of FCEVs differ depending on the vehicle type. It ranges from technical prototypes (TRL 5) in shipping and aviation to fully commercial FCEVs (TRL 9) like passenger cars or forklifts. A medium TRL of 6–8 can be assigned to commercial vehicles like trucks and buses. [ROL17] In order to exploit the full potential of the FC technology and to catch up with other solutions in terms of technical maturity, further research and development has to be conducted. To take part in the development, major automotive players invest in FC technology, but also younger companies explore the technology (see Fig. 22). Toyota has successfully developed and realized cost-reductions for the FC system (consisting of FC stack, air compressor, hydrogen pump, and tank) by a factor of 20 over the past ten years [FRI19].

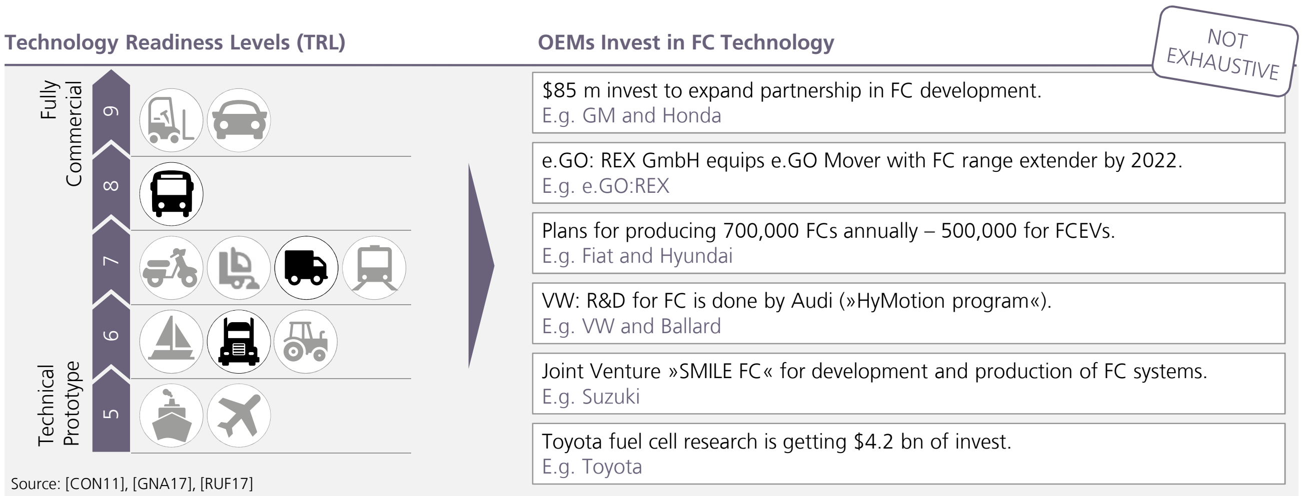


Fig. 22: Activities of Different Market Players Regarding FC Technology

DETAILED TECHNOLOGY ANALYSIS: PEMFC

A production-technological analysis of the various energy storage systems has been presented and outlined above. It has been pointed out that the low operation temperature and high energy density of PEMFC gives it a high potential for its application to vehicles. Furthermore, it was found that the high costs of PEMFC are a major drawback. Advancement of manufacturing technology and up-scaling is an efficient means for cost reduction and thereby achieving market diffusion. An analysis of the production process, consisting of component manufacturing as well as assembly processes, is an essential basis for technical development towards cost-efficient FC applications and therefore presented below.
In the beginning of this chapter, the main cost drivers, their rough cost structure as well as extent of cost reduction potential is pointed out. This is followed by a deep-dive in the individual production process of the key elements, namely BPP and MEA and their assembly. Here we discuss potential levers for cost reductions alongside with a further optimization potential.

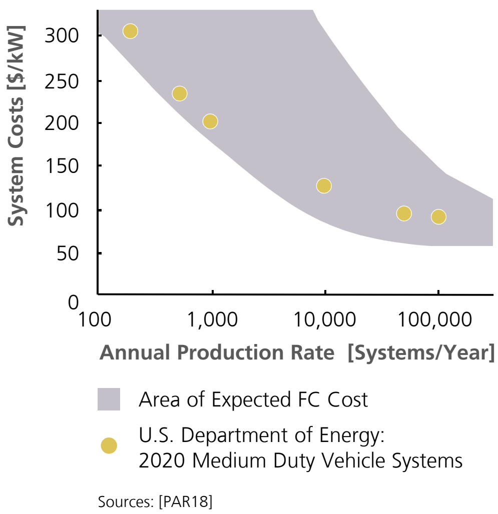


Fig. 23: Example for Upscaling Potential of FCs for Medium Duty Vehicle Systems in 2020

Cost Reduction Potential

The total cost reduction potential (depicted in Fig. 21) can be largely exploited by cost reduction of the stack, whose costs depend on the selection of manufacturing processes and materials on component level as well as on assembly processes. The predominantly manual production process of PEMFCs has the potential to leverage cost-reductions by automation. A high degree of automation is specifically possible for assembly. Furthermore, up-scaling of the total production is associated with a high cost reduction potential – although a certain

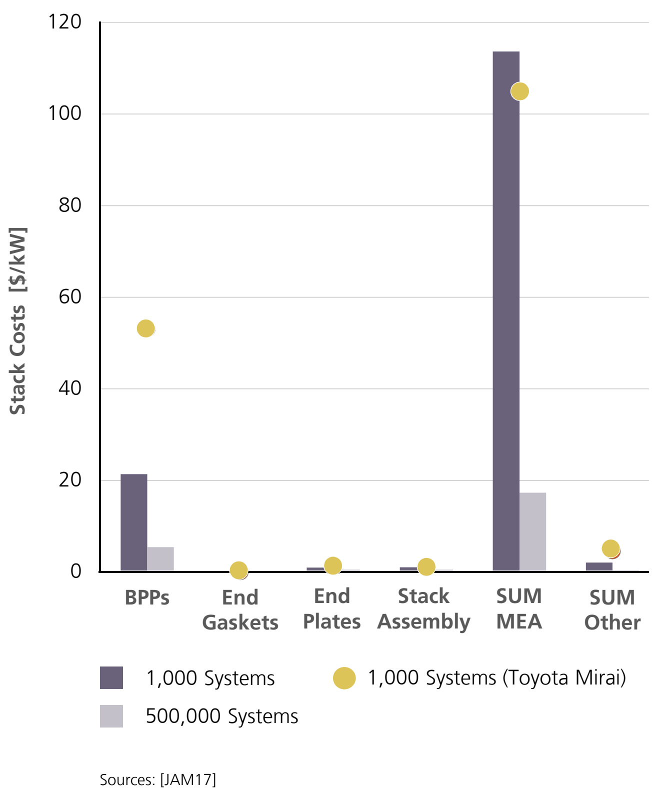


Fig. 24: Cost Estimation of Recommended Future Production Lines for Different Annual Stack Production Rates Compared to Actual Toyota Mirai Stack Production

degree of uncertainty in the forecast should definitely be considered (see Fig. 23) [PAR18].

Fig. 24 shows the cost estimation of recommended future production lines for an annual production rate of 1,000 stacks as well as for 500,000 stacks compared to cost estimation of actual Toyota Mirai stack production with an annual production rate of 1,000 stacks. It shows that on component level, the main cost drivers, and therefore the most important components to concentrate cost reduction efforts on, are the BPP and the MEA (Fig. 24). The distribution of manufacturing to material costs is about equal for the BPP compared to be below 1/10 for the MEA (see Fig. 25) [JAM16, BAT16]. MEA material costs represent the largest share. Even though MEA manufacturing costs only make up for 8 % of the MEA costs, they are nevertheless considerably high. Both, material cost reduction as well as manufacturing cost reduction in the BPP production are conceivable levers for a FC stack cost reduction as well. In the

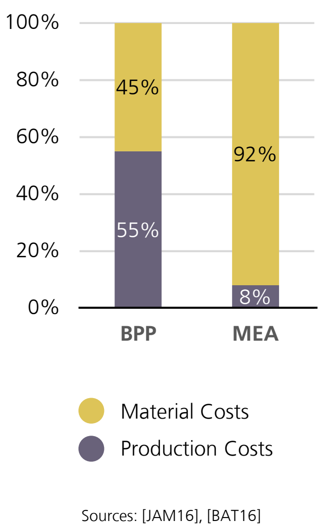


Fig. 25: Cost Structure of PEMFC Depending on Production Volume

following, manufacturing processes and technologies for the production of BPP and MEA are therefore to be envisaged.

Bipolar Plate (BPP)

The BBP manufacturing process starts with the production of a metal sheet by a rolling system. The melted metal is inserted between a series of rollers with parallel axes and squeezed into a sheet. [BEN10] In the second step, the flow field channels are applied to the metal sheets by using a micro-precision forming process such as stamping or hydroforming. The flow field channels of BPPs distribute the medium over the active surface and thus have an influence on the cell reaction. Thereafter, the plates are coated by either physical vapor deposition (PVD), also called sputtering, or chemical vapor deposition (CVD) coating. This coating process makes the BPPs corrosion-resistant and electrically conductive. [MEH03, TAH14] Release of ions from metallic BPPs, poisoning of the membrane, and as a consequence reduction of the FC performance is thereby inhibited. After forming and coating, two plates are joined together by laser welding. In this step, temperature-stable and corrosion-resistant markings can be applied to the BPPs using laser labelling. [LAS13]

Several challenges have been identified in the BPP production process. In the forming process, high accuracy is required for flow field channels. Deviation of channel height from specification can negatively affect cell operation. To avoid the installation of damaged cells into a stack, the deviation of channel geometry must be detected before the BPPs are mounted. [BEN10, MEH03] Moreover, expensive materials, namely gold or gold-plated titanium are currently used as coating materials of BPPs [TAG14, KUR16]. It is therefore necessary to find cost-effective materials for coating which nevertheless will create high corrosion resistance and electrical conductivity. In the joining process, laser welding will limit the output rate of the BPP production due to its low speed for the production of complex structures [FAR17, LAS13].

Membrane Electrode Assembly (MEA)

To produce a MEA, firstly catalyst ink, which usually consists of a platinum alloy, powdered carbon, nafion, distilled water, and methanol, are stirred in a ball mill process [BAT16]. For application of the catalyst layer, two different approaches are widely used: Catalyst Coated Substrate (CCS) and Catalyst Coated Membrane (CCM).

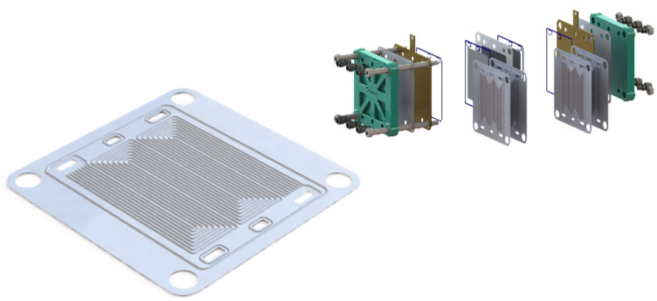
In the CCS approach, the catalyst is applied directly to the GDL so that Gas Diffusion Electrodes (GDE) are formed. Sputtering is one of several possible suitable coating process and calendaring can be used for the subsequent pressing of the GDE with the membrane. The anode and cathode are located on the GDL. Therefore, the PEM is inserted and joined with the GDL by hot pressing. After hot pressing of the membrane and GDL, the MEA is stamped into its final form, for instance by punching. [SIE15]

The CCM approach is characterized by applying the coating directly onto the membrane or indirectly via an intermediate substrate (decal). After application of the catalyst, the layer is

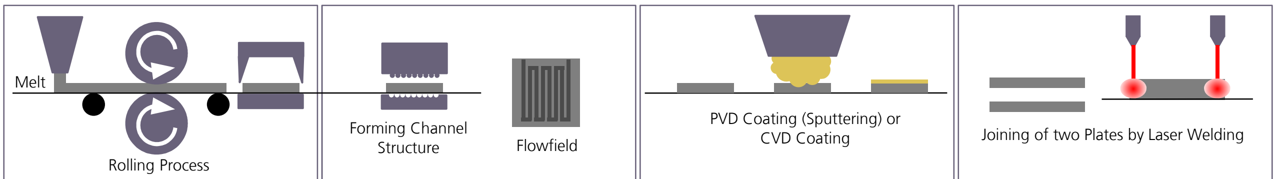
Technology Inside View
PEMFC – Bipolar Plate

Component Function

- Individual cells are separated with BBPs within a stack
- BPPs are used for electrical contacting of the electrodes
- Conduction of electrical current to adjacent cell
- Supply of fuels and, if necessary, cooling water as well as to dissipate heat and reaction products



Production of Metal Sheet	Forming of Flowfield	Coating	Joining



Challenges	Production of Metal Sheet	Forming of Flowfield	Coating	Joining
	■ Check for manufacturing defects to avoid tolerance violations ■ Deviations in plane-parallelism of both sides of the BPP must be compensated	■ High precision for reactant flow field required ■ Differing heights of channels can affect cell operation due to inhomogeneous media distribution ■ Different flowfield designs: microfluidics vs. formability	■ Expensive (coating) materials e.g. gold or gold-plated titanium ■ Expensive processes ■ Electrical conductivity and corrosion resistance as important parameter	■ Joining of a gas- and water-tight connection ■ Low distortion laser welding of cathode and anode plate ■ Reliable joining process for thin plates necessary

Sources: [BEN10], [DUN10], [FAR17], [IWU], [IUL], [KUR16], [LAS13], [MEH03], [PEN07], [TAH14]

Fig. 26: Technological Inside View of BPPs

dried. [FRO15] In the CCM-based direct approach, the anodes and cathode are located on the PEM. Then the GDL is placed and the PEM and GDL are joined using hot pressing. In the CCM-based indirect approach, the anode and cathode are located on the decal foil. The electrodes need to be transferred to the membrane, which is then pressed together with the GDL. [FRO15] Similar to the CCS approach, the final process step is to cut the MEA to its final shape [SIE15].

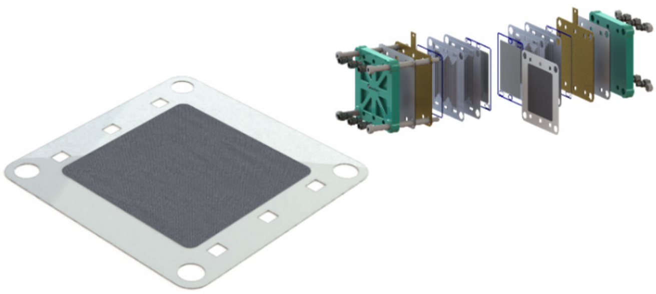
The challenges of the MEA production process are the catalyst layer application and hot stamping. During the application process of the catalyst layer, an optimization to achieve a continuous production of electrodes is necessary. Moreover, the development of inline production monitoring processes is required since defects such as holes and cracks in the catalyst layer can occur and limit the conductivity of the cell. [SIE15] In the hot pressing process, both process as well as material parameter optimization are required. This is due to the negative influence of the applied pressure and temperature on the integrity of the mechanical and electrical connection as well as on membrane and electrode material properties. [FRO15, FRA09]

Technology Inside View

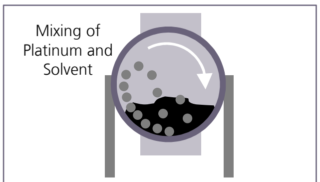
PEMFC – Membrane Electrode Assembly

Component Function

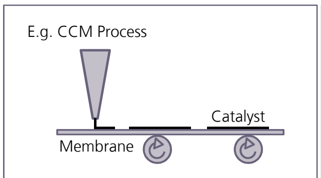
- Core component of FC, since this is the area of electrochemical reaction
- Composition by connecting membrane, catalyst and GDL
- CCM-based indirect approach: Electrodes are coated on a carrier or decal foil and then transferred to the membrane (decal process)



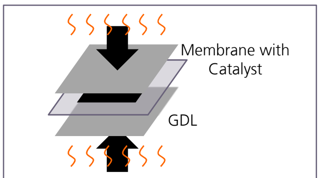
Mixture of Catalyst Ink



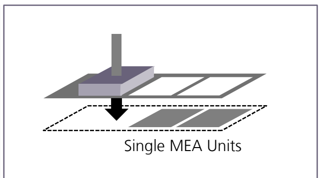
Application of Catalyst Layer



Hot Pressing of Membrane and GDL



Separation of Finished MEA



	Mixture of Catalyst Ink	Application of Catalyst Layer	Hot Pressing of Membrane and GDL	Separation of Finished MEA
Challenges	■ Highly complex due to the multitude of process parameters ■ Platinum amount is to be kept low due to high costs ■ Type of solvent has an influence on the rheological behavior of the catalyst ink	■ Material-efficient coating ■ Development of inline measurement methods for production monitoring ■ Defects such as holes and cracks in the catalyst layer can limit the conductivity of the cell	■ Wrong values of pressure and temperature can lead to significant material changes in membrane and electrode ■ Quality of the connection depends on process and material parameters	■ Stamping of single MEA units for subsequent stacking process

Sources: [BAT16], [FRÖ15], [FRA09], [KIS18], [SIE15]

Fig. 27: Technological Inside View of MEA

Sealing, Cell and Stack Assembly

Sealing of the stack is required to inhibit internal and external leakage as well as the compensation of tolerances induced by upstream manufacturing processes of components [ZBT19]. The sealing material has a high impact on the FC lifespan since it is the connecting part of MEA and BPP. The sealing is applied in a liquid or solid state. This requires application of pre-manufactured gasket layers or dispensing or injection molding [ZBT12]. The crucial part in this step is the precise handling and transport of the involved components. The curing of the gasket units involves temperature treatment in a continuous furnace [ZBT12]. The sealing performance depends on the material characteristics and the compression during stacking.

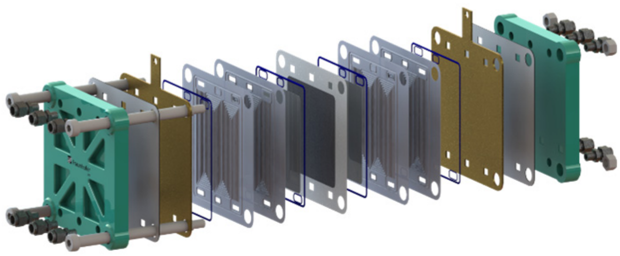
Then BPPs and sealing are joined together with the MEA by a pressing processe [ZBT12]. The MEA (either the membrane itself or the GDL) has been coated with a catalyst in the previous manufacturing step to amplify the PEM reactions in the

Technology Inside View

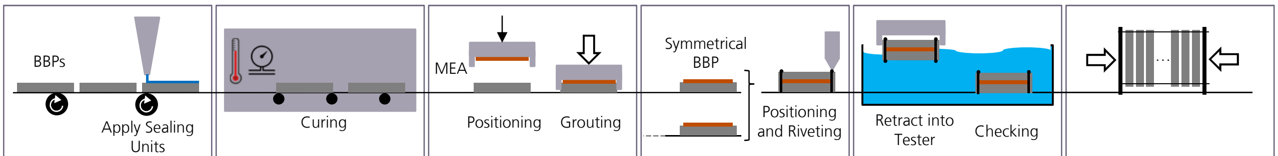
Proton Exchange Membrane Fuel Cell

System Overview

- Low-temperature FC with operating temperatures of 60 °C - 120 °C
- Structure of a PEMFC: An electrode catalyst material (E/K material), a GDL and a BBP are placed on both sides of a membrane
- To form a stack several cells are connected in series



Application of Sealings to BPP	Curing of Sealing	Application of MEA	Cell Formation and Fixation	Leakage Test	Stack Assembly



Challenges

Application of Sealings to BPP	Curing of Sealing	Application of MEA	Cell Formation and Fixation	Leakage Test	Stack Assembly
■ Simple and unambiguous installation of the sealing ■ Required chemical and thermal resistance ■ Low electrical conductivity	■ Optimization between preventing hydrogen release and compensating manufacturing tolerance ■ High reaction forces in sealing not permitted	■ Precise positioning of BBP and MEA ■ Reliable joining of components ■ Automation of MEA handling difficult	■ Compliance of tolerances ■ Demand-compliant positioning ■ Shortening of lead time	■ Safety relevance ■ Risk of explosion if hydrogen reacts with air	■ Various stack concepts possible ■ Choice of material combination ■ Homogenization of contact pressure

Sources: [BAT16], [BEN10], [BLO05], [CAR14], [KEM05], [KUR16] [ZBT12], [ZBT19]

Fig. 28: Detailed Technological View of PEMFC

stack (for further information see MEA production [BAT16]). In these steps, very precise handling of the components and leakage-preventing joining of the plate and MEA are necessary.

The next steps include the final FC formation and fixation. Additional BPPs are placed precisely onto the half-ready FCs by robots or gripper technologies from a carriage system. High precision automation is the crucial factor for a successful cell closing.

The finished FCs are then extensively inspected by water bath testing, pressure testing, or exposure to gas for its sealing functions [BLO05]. If needed, optical controls and selective sensor technology are implemented [ZBT12]. The FC working must be guaranteed in a reliable manner for safety when used in mobility applications. An automated test stand is used to test the differential pressures and characteristic channel structures (flow fields).

If controlled successfully, the FCs are connected in series to form the FC stack [BEN10]. Two end plates close the stack that consists of several hundred FCs and provide adapters for the electric current as well as the gas and cooling water [BAT16]. These steps involve high precision handling and assembly processes with a high demand of automation. Cost efficiency and reproducibility are the most important design factors of these steps.

Key Takeaways for the Manufacturing Industry

- High precision technology is required for the forming and joining of BPPs due to the material thickness.
- Challenges for the coating of BPPs are high coating material costs and long process durations.
- Development of monitoring processes is required in the catalyst layer application process for MEA manufacturing.
- Process and material parameter optimization are required in the hot pressing process for MEA manufacturing.
- Implementation of automated processes is required to achieve high production rates.

THE ROLE OF FRAUNHOFER IPT

Despite recent developments in FC technology, FCs have not yet reached the technological and economical maturity which is required for serial production and economic competitiveness. Further research is needed to reach a sufficient TCO level as well as high technical reliability, low maintenance efforts, long life-time and a higher TRL (see Fig. 29). Many of these challenges are connected to production technology of the FCs. To support the shift from small manufacturing operations to large-scale FC production facilities, production-technological challenges must be overcome.

Due to the rather low TRL (see Fig. 22), the PEMFC has a significant development potential in terms of production technology. To support the shift from small manufacturing operations to large-scale FC production facilities, production-technological challenges must be overcome.

Gaining control over the pending technological challenges (see Fig. 29) is a key factor for the up-scaling of the FC production and thereby making the FC a competitive alternative to other energy storage and drive solutions. The forming of the metallic BPPs is particularly challenging because they are made from thin metal sheets with a high degree of deformation. Efficient FC stacks require high accuracy and repeatability of the forming process. Fraunhofer IPT can rely on expertise in most fields of production technologies relevant for FC manufacturing such as process chain optimization, tooling, equipment, and high precision measurement. When joining two adjacent BPP halves, the discharge of heat while laser welding has to be monitored. The institute has significant experience with laser-based processes, particularly in the development of necessary equipment and quality control. Additionally, Fraunhofer IPT can make use for the coating process, of profound knowledge of methods, equipment, and quality control. For the FC production, the metallic BPPs need to be coated to avoid corrosion and decrease contact resistance. Also for the MEA, coating can be used as a lamination process. The coating needs to be as thin as possible while also being robust. FCs are layered over each other repeatedly to build a stack according to the desired properties. This allows for the up-scaling of the technology. Concerning the precise handling required to layer the components properly, Fraunhofer IPT can provide expertise in handling technology and position measurement. The high demand for identical key components such as BPPs indicates a potential for economies of scale, especially in highly automated mass production and emphasizes the need for a detailed investigation of the technology. For this reason, Fraunhofer IPT continues research in the fields of metal forming, processing, handling, and joining to master the required and critical processes for technology development of FCs. Furthermore, the developed technology will provide support for industrial series production of the FC stack, its components, and associated peripheral systems.

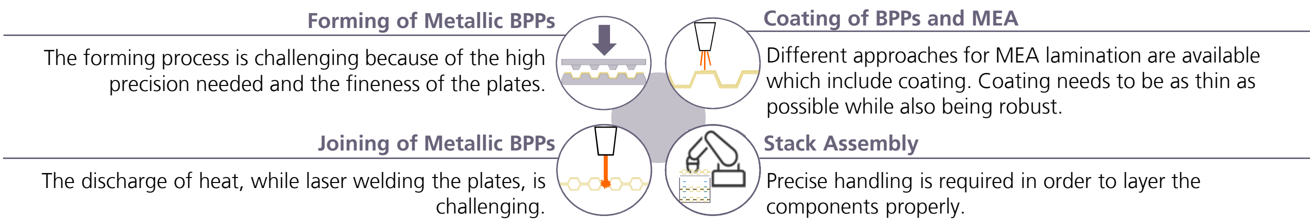


Fig 29: The Role of Fraunhofer IPT - Surpassing Production-Technological Challenges

OUTLOOK

The different requirements of cars, vans, buses or trucks clearly show the need for a wide range of technical solutions. Especially long-range buses and trucks are use cases, in which advantages of BEVs are exceeded by the advantages of FCEVs – namely cost advantages in case of high range requirements. Even a hybrid solution that incorporates the advantages of LIB and FC storage technology offers possibilities to optimize the efficiency of the powertrain. This holds true now, and is amplified when the cost reduction potential of FC production is applied.

In the next Discussion Paper "The Relevance of Fuel Cell for Mobility Applications", we implement the development of the reference production process for FC production. Firstly, the technical requirements of each commercial vehicle segment are analyzed in terms of engine power, driving range, and uptime. As a next step, a specific business case is considered based on the specific vehicle segment to evaluate whether the selected vehicle segment also can represent significant market sales. Moreover, results from the conducted technology and manufacturing process studies allow for the definition of several production line options. Insights about specifications of all process steps from the general production line configuration are used to explore different design options. In combination with the selected use cases and derived stack and tank design, the reference production line is developed. Challenges are identified in order to iteratively optimize the process chain. On the one hand, a process-oriented deep dive is mandatory in order to realize future cost saving potentials as well as benefits from up-scaling effects. On the other hand, a production-oriented deep dive is essential to understand the implications of production increases. All in all, this approach ultimately allows a conclusion on the manufacturing challenges and technology development needs in automated FC series production and on the part of the machine suppliers. In a mid-term period, further developments in terms of production technology enable an increase in TRL and a decrease in TCO for the use of the case-specific FC design selected. This is crucial for establishing the technology as a competitive alternative to conventional solutions.

LIST OF FIGURES

ACRONYMS

AESC Automotive Energy Supply Corporation
AFC Alkaline Fuel Cell
BEV Battery Electric Vehicle
BMS Battery Management System
BPP Bipolar Plates
CARG Compound Annual Growth Rate
CCM Catalyst-Coated-Membrane
CCS Catalyst-Coated-Substrate
CNC Computerized Numerical Control
CO_2 Carbon-Dioxide
CVD Chemical Vapor Deposition
DMFC Direct Methanol Fuel Cell
EDLC Electrochemical Double Layer Capacitor
ETH Swiss Federal Institute of Technology in Zurich
EU European Union
FC Fuel Cell
FCEV Fuel Cell Electro Vehicles
FRP Fiber Reinforced Plastics
FW Flywheel
GDE Gas Diffusion Electrodes
GDL Gas-Diffusion Element
GHG Greenhouse Gas
GSE Ground Support Equipment
LIB Lithium-Ion Battery
MCFC Molten Carbonate Fuel Cell
MEA Membrane Electrode Assembly
MIT Massachusetts Institute of Technology
NO_x Generic Mono-Nitrogen Oxides
OEM Original Equipment Manufacturer
PAFC Phosphoric Acid Fuel Cell
PEM Proton Exchange Membrane
PEMFC Proton Exchange Membrane FC
PHEV Plug-In Hybrid Electric Vehicle
PVD Physical Vapor Deposition
SC Supercapacitor
SOFC Solid Oxide Fuel Cell
SSB Solid-State Battery
TCO Total Cost of Ownership
TRL Technology Readiness Level
UPS United States Parcel Service

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ISBN 978-3-00-065452-7
DOI: 10.24406/ipt-n-590461