Resources, Conservation & Recycling Advances 19 (2023) 200172

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

Challenges and prospects of automated disassembly of fuel cells for a circular economy

Anwar Al Assadi [a,*], Dominik Goes [c,*], Sabri Baazouzi [a], Malena Staudacher [d], Piotr Malczyk [e], Werner Kraus [a], Frank Nägele [a], Marco F. Huber [a,b], Jürgen Fleischer [c], Urs Peuker [d], Kai Peter Birke [a,f]

[a] Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, Stuttgart 70569, Germany
[b] University of Stuttgart, Institute of Industrial Manufacturing and Management IFF, Allmandring 35, Stuttgart 70569, Germany
[c] wbk Institute of Production Science, KIT Karlsruhe Institute of Technology, Kaiserstraße 12, Karlsruhe 76131, Germany
[d] Institute of Mechanical Process Engineering and Mineral Processing, Technical University Bergakademie Freiberg, Agricolastraße 1, Freiberg 09599, Germany
[e] Institute of Ceramics, Refractories and Composite Materials, Technical University Bergakademie Freiberg, Agricolastraße 17, Freiberg 09599, Germany
[f] Chair for Electrical Energy Storage Systems, Institute for Photovoltaics, University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany

ARTICLE INFO

Keywords:
Robot-based disassembly
Circular economy
Fuel cell

ABSTRACT

The hydrogen economy is driven by the growing share of renewable energy and electrification of the transportation sector. The essential components of a hydrogen economy are fuel cells and electrolysis systems. The scarcity of the resources to build these components and the negative environmental impact of their mining requires a circular economy. Concerning disassembly, economical, ergonomic, and safety reasons make a higher degree of automation necessary.

Our work outlines the challenges and prospects on automated disassembly of fuel cell stacks. This is carried out by summarizing the state-of-the-art approaches in disassembly and conducting manual non-/destructive disassembly experiments of end-of-life fuel cell stacks. Based on that, a chemical and mechanical analysis of the fuel cell components is performed. From this, an automation potential for the disassembly processes is derived and possible disassembly process routes are modeled. Moreover, recommendations are given regarding disassembly system requirements using a morphological box.

1. Introduction

The enormously high gravimetric energy density of hydrogen makes it the preferred energy carrier of the future. The energy density of liquid hydrogen is around three times that of petroleum and diesel (Züttel et al., 2010). Due to the fluctuating power supply of renewable energy and the growing electrification of the transport sector, new energy carriers are needed (Abbasi and Abbasi, 2011; Manoharan et al., 2019). For this reason, fuel cell systems and electrolyzers play a great role in a hydrogen economy (Edwards et al., 2008). With the aid of fuel cells, hydrogen H_2 and oxygen O_2 are converted into water H_2O, while an electrical current flows during the process (Züttel et al., 2010). Therefore, fuel cells in combination with gas tanks and electric engines are being considered as a possible power train for electrification of the transport and non-transport sector (e.g., agricultural and construction machinery) (Bernard et al., 2009; Lajunen et al., 2018). Other promising applications are (micro) combined heat and power units (CHP). Over 100,000 such units have been installed in Japanese households (Olabi et al., 2020). With increasing production capacities of fuel cells, the recovery of the raw materials used will become more important in the future (Clifford, 2023). The criticality of the raw materials themselves and a sustainability requirement associated with hydrogen technology are motivation for the development of an adapted circular economy. Disassembly is considered the first step in the process chain of the various circular economy strategies such as recycling, remanufacturing, or reuse. In order to realize an economic circular economy, disassembly must be automated in the future. However, expected and required process steps/tools and challenges in the automated disassembly of fuel cell stacks still need to be sufficiently discussed. That means a qualitative overview of the product state (e.g., corrosion, material condition, and joining techniques) at the end of life (EoL) has to be compiled by conducting manual disassembly experiments. For this, a standardized

* Corresponding authors.
E-mail addresses: anwar.alassadi@ipa.fraunhofer.de (A. Al Assadi), dominik.goes@kit.edu (D. Goes).

https://doi.org/10.1016/j.rcradv.2023.200172
Received 24 January 2023; Received in revised form 9 June 2023; Accepted 12 July 2023
Available online 17 July 2023

scheme is missing to collect the (practical) product requirements for the design of robotic disassembly cells. The subsequent examination of the materials in terms of composition is required to evaluate the effort for the circularity.

The paper is organized as follows: The following section summarizes background information on fuel cell technology and the associated raw material issues (Section 2). Section 3 provides an overview of related work in terms of disassembly types and techniques. Section 4 clarifies the materials and methods of this work. Subsequently, the results of the manual disassembly, component analysis and the automation concept are presented in Section 5. The discussion of our work is stated in Section 6. Finally, Section 7 concludes this paper and gives a brief outlook on future work in this field.

2. Background

This section provides a brief overview of fuel cell technology, including the costs of a fuel cell stack, stack structure and aging phenomena of the individual components. Furthermore, an overview of the raw materials used in fuel cells is provided.

Fuel cell technology

There are various types of fuel cell technologies. However, proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) show a promising prospect for mobile and stationary applications, respectively (Steele and Heinzel, 2011). PEMFC stacks are commonly used as energy converters for mobile applications in vehicles. Together with the peripheral components, also called balance of plant, they constitute the fuel cell system. According to the cost model of Kampker et al., the production costs of a PEMFC system at an output quantity of 30,000 systems per year (this is the production capacities announced by Toyota in 2020) are about 235 EUR/kW (Clifford, 2023). In contrast, the production costs for SOFC stacks from the Forschungszentrum Jülich for stationary applications are estimated by Harboe et al. at 1210 EUR/kW for a production volume of 25 MW. The stack design of both fuel cell technologies is illustrated in Fig. 1. The core of the system consists of stacked cells, which are called fuel cells. Regardless of the fuel cell technology, these fuel cell stacks are composed of several cells. Each individual cell consists of a hydrogen electrode and an oxygen electrode. Between the electrodes an ion conducting electrolyte layer separates each reacting space (Kurzweil, 2012). A contact layer adjacent to the electrodes ensures the distribution of the reactants and reaction products and the conduction of electrons from the catalysts to the current collector plate (Harboe et al., 2020; Rashapov et al., 2015). This current collector plate isolates the individual cells from each other and thus prevents the mixing of the different reaction gases. It also provides the electrical connection between the various single cells (Taherian, 2014; Wu and Liu, 2010). Several of the layers mentioned are additionally coated with a protective layer. Sealings both provide a seal against the environment and prevent the mixing of the reactants (Fergus, 2005; Husar et al., 2007). The stack is compressed. End plates at the outer ends of the stack provide the compression. For adjusting the clamping force connecting techniques such as tie-rods or band connectors are used (Kim et al., 2008; Liu et al., 2016).

PEMFCs features the following components: a bipolar plate (BPP) that operates as a current collector and also induces the fluid flow through a so-called flow field (Kim et al., 2018), a gas diffusion layer (GDL) that operates as a contact layer, a catalyst coated membrane (CCM), another gas diffusion layer followed by the next bipolar plate. The CCM comprises a proton exchange membrane (PEM) sandwiched between two catalyst layers (CL). The GDL's and the CCM constitute the membrane electrode assembly (MEA). Thereby a PEMFC stack is composed of the two repeating units, the MEA and the BPP. These structure, including the sealings, represent a single cell (Schäfer et al., 2021; Song et al., 2022). Depending on the sealing concept, the sealing can be applied to the BPP or it is a part of the MEA compound. Due to the comparatively low operating temperature around 80°C compared to other fuel cell technologies, PEMFCs require the use of catalysts containing noble metals. The catalysts in PEMFCs are therefore preferably based on platinum group metals (Töpler and Lehmann, 0000). The membrane is made of a polymer, consisting of polytetrafluoroethylene (PTFE). The thus hygroscopic membrane expands and contracts due to fluctuations in humidity and temperature. It is therefore often framed in subgaskets to constrain the dimensional changes of the membrane and increase mechanical stability (Ma et al., 2022). PEMFC applications

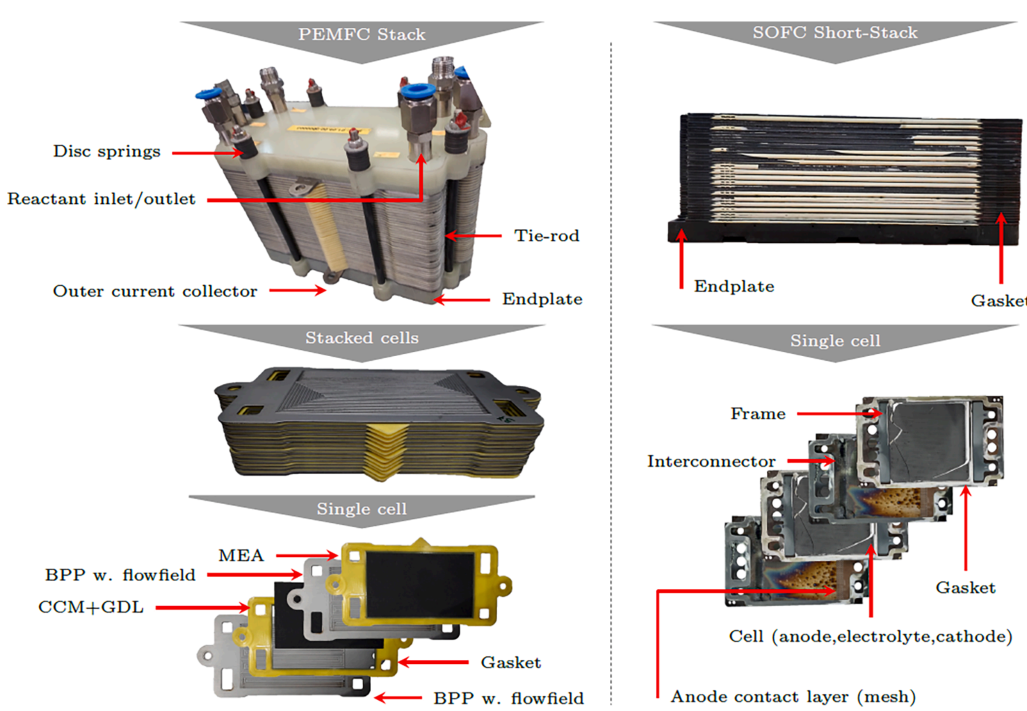


Fig. 1. Design of a PEMFC and a SOFC from the stack to a single cell.

generally require adequate performance to be maintained over long periods. The United State Department of Energy (DOE) has issued a lifetime target of 8000h for PEMFC stacks for light-duty vehicles and 30.000h for PEMFC stacks for heavy-duty trucks (US Department of Energy, 2023). The stacks reach the end of their life due to various degradation phenomena under dynamic and harsh operating conditions. These conditions include starting and stopping, impurities in the fuel and air and humidity and dynamic load cycle that result in stresses on the chemical and mechanical stability of materials and components. Wu et al. provides an overview of the major failure modes of the different components in PEMFCs. With regard to the MEA, mechanical and chemical/electrochemical degradation can lead to so-called pinholes, resulting in early membrane failure. In the case of the bipolar plate, corrosion or deformation predominates.

SOFCs, in contrast, are principally constructed using the following components: An interconnector, an anode contact layer usually in the form a nickel-mesh, the anode followed by the electrolyte and cathode, a cathode contact layer usually in the form of a ceramic layer followed by the next interconnector. Especially the cell layers like anode, electrolyte, and cathode become one unit by sintering processes. Depending on the cell design, a metallic or ceramic-based support layer is commonly used (Maric and Mirshekari, 2021). Each cell is framed by the cell frame. This structure build the cell frame unit. A sealing, often made of glass ceramic composites, is placed between each cell frame unit and interconnector (Harboe et al., 2020; Kennouche et al., 2018). The described assembly represents one single repeating unit (SRU). SOFC stacks are formed by many stacked SRUs and are operated at high temperatures between 600°C and 1000°C (Maric and Mirshekari, 2021). This high operating temperature supports rapid electrocatalysis with non-noble metals (Stambouli and Traversa, 2002). However, due to the high operating temperatures, the components of SOFCs require high durability. Therefore, rare earths are used as SOFC materials because they have good chemical stability, are resistant to high operating temperatures, and provide oxide ion conductivity (Li et al., 2020b; Sakai et al., 2005). SOFC stacks can achieve runtimes of up to 45000 h in stationary applications (Bosio and Bianchi, 2023). Various aging phenomena such as voltage degradation, interdiffusion, foreign phase formation, oxidation, or fracturing can result in reduced cell performance and lead to the complete failure of the stack (Sarner et al., 2022).

Raw material

Around 30 materials are needed for the production of fuel cells. Since 2011 the European Commission has been publishing a critical raw material list (Bobba et al., 2020). For fuel cells, the materials cobalt, magnesium, REEs, platinum, palladium, borates, silicon metal, rhodium, ruthenium, graphite, lithium, titanium, and vanadium are identified as critical in terms of supply risk, deposits, and economic importance (Bobba et al., 2020). Therefore, circular economy approaches are needed to close the loop of material consumption. In this context, several circularity strategies can be applied at different phases of the product life cycle. They can be divided into three categories (Potting et al., 2017): (1) smarter product use and manufacture, (2) extended lifespan of the product and its parts, and (3) useful application of materials. Disassembly is essential for implementing the most relevant circular economy strategies, especially at the end-of-life phase for remanufacturing, repurposing, and recycling (Glöser-Chahoud et al., 2021). Figure 2 illustrates the product flow through a circular economy.

3. Related work

In this section, a brief overview is given about the related work. In doing so, publications regarding the general disassembly types and techniques for automated disassembly approaches are summarized.

3.1. Disassembly types

Several publications dealt with disassembly in the last years. Thereby, four main research fields can be distinguished (Glöser-Chahoud et al., 2021; Laili et al., 2020). These are disassembly planning (DP), disassembly sequencing (DS), disassembly line balancing (DLB), and disassembly techniques (DTs). DP deals with forecasts to make decisions considering the quantity, timing, quality, and location of returns (O'Shea et al., 1998). Dealing with the uncertainties in the mentioned parameters represents a significant challenge to plan the needed capacities and evaluate the economic efficiency of the disassembly and the subsequent processes needed for implementing the appropriate circular economy strategy (Jin, 2016). DS is a prominent research field in the context of disassembly. It deals with determining the optimal disassembly sequence of a given product and is not only relevant for automated disassembly solutions (Gungor and Gupta, 1998; Vongbunyong et al., 2015). Ke et al. showed that the disassembly time could be reduced by more than 10% using disassembly sequencing methods in manual disassembly operations. A field study of Rosenberg et al. assesses the disassembly time of a battery system of a hybrid electric vehicle. Their results indicate an approximate time of 22 min. Wegener et al. neglected the disassembly time, which is essential for an economic assessment (Lander et al., 2021). However, Rallo et al. considered the disassembly time in terms of reusing battery systems to show the economic feasibility. DLB deals with assigning disassembly tasks to different workstations in a disassembly line. In literature, several DTs can be found. According to Baazouzi et al., the mechanical system of a disassembly station consists of three main components. These are manipulators such as robot arms, tools to carry out the disassembly

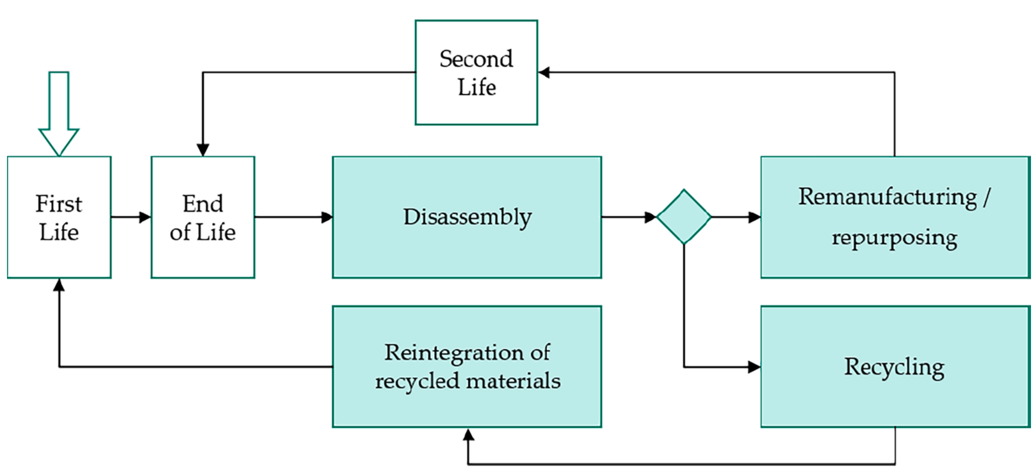


Fig. 2. The disassembly as key technology to implement circular economy solutions, adapted from Glöser-Chahoud et al. (2021).

operations, and handling devices.

Disassembly can be carried out using several modes, compare Table 1. Regarding the disassembly depth, complete and incomplete disassembly can be distinguished. The complete disassembly can be limited to removing all subassemblies but can involve further disassembling. However, incomplete disassembly includes the removal of specific components only. Here, there are different methods for selecting the parts. A direct selection of target parts (high value or high impact parts) can be used (Ren et al., 2017). In addition, the optimal disassembly depth can be the result of a single (Go et al., 2012; Yeh, 2011) or multi-objective (Alfaro-Algaba and Ramirez, 2020; Ren et al., 2020; Wu et al., 2022; Yu-fei and Qiang, 2016) optimization.

Moreover, disassembly methods can be divided into non-destructive, semi-destructive, and destructive methods. The non-destructive disassembly is the most challenging, as all joining techniques must be detached without destruction. This can be very time-consuming and involves the use of many tools. Non-destructive disassembly can be profitable if the components are subjected to high-quality circular economy strategies such as remanufacturing. Semi-destructive disassembly takes place when the joining elements (screws) and/or selected parts (plastic components that must be recycled) are removed destructively, using, for instance, cutting and milling tools (Hjorth and Chrysostomou, 2022; Nave, 2003).

Depending on the number of manipulators used, disassembly can be performed either sequential when the components are removed one by one or in parallel if more than one part can be disassembled simultaneously (Zhou et al., 2019). In Ren et al. (2018), two types of parallel disassembly are mentioned: synchronous parallel disassembly, where all manipulators start new tasks simultaneously, and asynchronous parallel disassembly, where manipulators can start the next assigned task immediately after finishing the previous task.

Currently, the disassembly of complex products such as electric vehicle batteries is carried out manually, leading to a bottleneck in processing products at the end-of-life phase (Yun et al., 2018). Moreover, the disassembly of fuel cells poses safety risks to human workers. For these reasons, the automation level of partially or fully automated solutions is essential to push future circular economy solutions for fuel cells.

The selection of the disassembly mode depends on the product design, the state of the components, and the materials used. Besides, it affects the economic and environmental performance of the disassembly process. Therefore, conducting manual disassembly experiments of end-of-life fuel cell stacks is essential to determine the appropriate disassembly modes for these products, find out the challenges and perspectives on automated disassembly of fuel cell stacks, and derive the automation potential for the disassembly process. In Wittstock et al. (2016) the challenges in automotive fuel cell recycling have been discussed. However, there are still gaps regarding potential solutions for automated disassembly of fuel cell stacks and the associated practical challenges.

3.2. Disassembly techniques

As was mentioned in the previous section, several works dealt with techniques to automate the disassembly. Recent research activities consider products such as motor engines, battery systems from electric vehicles, laptops, hard disk drives, automotive water pumps, and turbochargers (Bdiwi et al., 2016; Choux et al., 2021; DiFilippo and Jouaneh, 2017; Gerbers et al., 2016; 2018; Huang et al., 2020; Klas et al., 2021; Li et al., 2020a; Rastegarpanah et al., 2021; Schmitt et al., 2011; Wegener et al., 2015; Weyrich and Wang, 2013; Zorn et al., 2022). Additional research activities have also been conducted in the 1990s/2000s. These research activities has covered products such as car wheels (Büker et al., 2001), washing machines (Seliger et al., 2001), electric motors (Karlsson and Järrhed, 2000), air conditioner and washing machines (Uchiyama et al., 1999), Televisions (Nave, 2003; Scholz-Reiter et al., 1999), printed circuit board (PCB) (Knoth et al., 2002), personal computer (PC) (Hohm et al., 2000) and car components (Knackfuss and Schmidt, 1996). The main processes studied are detection using (3D/2D) sensors to localize and/or correct position, handling components, and separation of joining techniques. In these works, fully automated (Büker et al., 2001; Feldmann et al., 1999; Knackfuss and Schmidt, 1996; Nave, 2003; Scholz-Reiter et al., 1999) and partially automated disassembly approaches (Hohm et al., 2000; Karlsson and Järrhed, 2000; Knoth et al., 2002; Seliger et al., 2001; Uchiyama et al., 1999) are proposed. However, the studies attempt to have relatively big, stiff, and non-porous components. Opposing properties are requirements for fuel cell stacks disassembly. The existing principles and approaches for localization and handling in (dis)assembly literature could help to develop an automated robot-based disassembly cell. In terms of manual disassembly Kroll et al. presented a methodology to evaluate the ease of manual disassembly. However, this methodology neglected automated robotic cells' requirements and design aspects for disassembly. Waldmann et al. presented an overview of state-of-the-art methods for disassembling aged Li-ion battery cells. Battery cells are comparable to fuel cells due to their layered structure. Challenges for disassembly are identified, and requirements for the disassembly process and disassembly tools are made. However, no implementation of automated disassembly is proposed. A highly experienced experimenter using the appropriate equipment for cell opening is mandatory. Marshall et al. also provide a method for manual disassembly of battery cells. According to the authors, automation is necessary and would allow this process to be scaled up. Comprehensive overviews of automated disassembly are given in Poschmann et al. (2020), Meng et al. (2022), where Meng et al. considers artificial intelligence approaches. Most of these approaches pursue robot-based automation for disassembly, where typical process steps include localization of joining such as screw (Bdiwi et al., 2016; DiFilippo and Jouaneh, 2017), unfastening screws, (DiFilippo and Jouaneh, 2017; Gerbers et al., 2016; Li et al., 2020a; Nave, 2003), unfastening nuts (Rastegarpanah et al., 2021) and handling (Klas et al., 2021; Schmitt et al., 2011). Works like (Choux et al., 2021; Weyrich and Wang, 2013; Zorn et al., 2022) propagate a computer version-based approach for the localization, also serving as a base for the

Table 1
Overview of the possible disassembly modes, inspired by Zhou et al. (2019), Vongbunyong et al. (2015).

Disassembly mode	Alternative					
Disassembly depth	Complete part level	Complete, subassembly level	Incomplete, selective high value strategy	Incomplete, selective high impact strategy	Incomplete, unrestricted single objective	Incomplete, unrestricted multi-objective
Disassembly method	Non-destructive	Semi-destructive: joining components	Semi-destructive: joining components and selected parts		Destructive disassembly	
Disassembly sequence		Sequential	Parallel		Parallel asynchronous	
Automation level	Manual	Partially automated: Human machine collaboration	Partially automated: No collaboration		Fully automated	

disassembly task planning. Wegener et al., Gerbers et al., Huang et al., Li et al. propose a Human-Robot-Collaboration for the disassembly. Major drawbacks of those approaches are the single process focus without deep product EoL conditions, the missing highlights about possibly recoverable materials, and the systematic design of an automated flexible disassembly robot cell.

4. Materials and methods

In this section, the manual disassembly, which serves as input for automation concept and the disassembled samples are introduced. Additionally, the chemical analyses are outlined. Figure 3 summarizes the structure of this work.

4.1. Manual disassembly

The analysis of the manual disassembly has been carried out similar to Wegener et al.. In Wegener et al. only the following aspects have been documented during the disassembly: disassembly sequence, disassembly step, and required tools. However, this work extended the list by essential properties and derived automation aspects regarding the future conception and implementation of an automated disassembly solution, compare Table 2. These aspects serve as starting point for the application of VDI2221 for the design of technical products and systems (VDI2221, 2019).

4.2. Disassembled samples

The manually conducted disassembly experiments included three fuel cell stacks. The external appearance shows signs of use. The stack's physical characteristics and operating conditions are given in Table 3. The two PEMFC stacks are complete, including the two end plates and compression elements such as tie rods. One of the two stacks also contains connections on the upper-end plate for the supply and removal of reactants and products. In both PEMFC stacks, the sealing concept provides the sealing to be part of the MEA compound. The SOFC stack is a short-stack and was developed and manufactured by the Forschungszentrum Jülich. It contains the lower end plate and five stacked cells without compression elements and media connections. All stacks investigated were in operation, showed signs of aging and have been used at a research facility. The disassembled sample stacks represent the basic product structure of PEMFC and SOFC stacks, compare also (Kim et al., 2008).

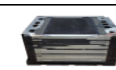
4.3. Analysis methods of disassembled components

The analysis of MEAs' composition and structure was carried out with the help of Scanning Electron Microscopy with Energy-dispersive X-Ray Spectroscopy (SEM/EDS) using Philips XL30 SEM with EDAX-EDS (Philips FEI Deutschland GmbH, Germany) with an accelerating voltage of 20kV. The structure of MEA was analyzed on the sample cross-sections revealing the thickness of each layer, such as GDL, electrode, and membrane. The composition of electrodes was estimated on the untreated electrode material free of GDL residuals. For the purpose of composition estimation, the spectrum from each electrode side via area scan (surface size $> 500 \mu m^2$) was collected. For analysing the composition of end plates and bipolar plates FT-IR spectroscopy (Nicolet 5 Thermo Fisher Scientific Inc., United States) was used. The two different analysis methods must be chosen because massive components such as the end plates and bipolar plates are too large for other methods. In contrast, the MEA can be cut to small sample sizes. An analysis of the structure, the components and the materials of the SOFC stack of the Forschungszentrum Jülich is already presented in Harboe et al. (2020).

Table 2
The acquired properties and the associated derived aspects for automation.

Component property	Derived automation aspect
Material stiffness (yes/no)	Gripper principle
Magnetic (yes/no)	Gripper principle
load m / kg	robot payload & Gripper property
Dimensions $l \times h \times w$ / mm	Gripper property
Joining technology	Required disassembly tool
Reversibility (yes/no)	Required disassembly tool
Approximate time t / s	Expected cycle time
Required number of hands	Robot numbers, required disassembly tool peripheral components

Table 3
The sample overview of the manual disassembly.

Description	Stack 1	Stack 2	Stack 3
Stack			
Type	PEMFC	PEMFC	SOFC
Dimension $l \times w \times h$ / mm	278 × 130 × 164	570 × 180 × 250	370 × 225 × 50
Cell numbers	40	120	5
Active surface $a \times b$ / mm	154 × 92	202 × 110	200 × 200
load m / kg	≈ 10	≈ 35	≈ 17
Assembly year	N/A	2004	N/A
Operating hours t / h	4000	550	550

5. Results

In this section, the results of the manual disassembly are summarized. The encountered challenges regarding an automated solution are highlighted. Furthermore, the chemical analysis and conception for an automated approach are presented.

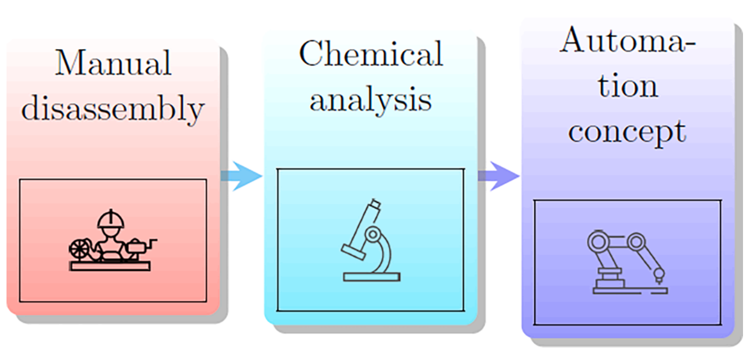


Fig. 3. The structure of this work.

Table 4
The disassembly steps of stack 1.

Nº	Disassembly step	Required tools	Stiffness (yes/no)	Magnetic	Mass m / g	Dimensions $l \times h \times w$ / mm	Joining technology	Reversibility	Approx. Time t / s	Required number of hands
1	Remove paste	Hand	No	No	-	-	Adhesive bond	No	30	1
2	Unfasten nuts	Wrench	Yes	Yes	10	M6	Force-locked	Yes	290	2
3	Remove washer/disc springs	Hand	Yes	Yes	4	$12 \times 12 \times 1.6$	Force-locked	Yes	2	1
4	Unstack the endplate (1st)	Hand	Yes	No	801	$278 \times 130 \times 21$	-	Yes	2	2
5	Unstack current collector	Hand	Yes	No	170	$278 \times 130 \times 2$	-	Yes	2	2
6	Unstack flow field	Hand	Yes	Yes	12	$278 \times 130 \times 1.1$	Adhesive bond	No	2	2
7	Unstack membrane electrode assembly	Hand	No	No	22	$278 \times 130 \times 1.7$	-	Yes	2	2
..			repeatable steps, depends on the number of cells							
n-1	Unstack the endplate (2nd)	Hand	Yes	No	801	$278 \times 130 \times 21$	-	Yes	2	2
n	Remove thread rod	Hand	Yes	Yes & No	60	595	plug connection	Yes	4	1

Table 5
The disassembly steps of stack 2.

Nº	Disassembly step	Required tools	Stiffness (yes/no)	Magnetic	Mass m / g	Dimensions $l \times h \times w$ / mm	Joining technology	Reversibility	Approx. Time t / s	Required number of hands
1	Remove plastic caps	Box cutter	No	No	3	-	-	No	30	1
2	Unfasten nuts (1st row)	Wrench	Yes	Yes	10	M10	Force-locked	Yes	300	1
3	Unfasten nuts (2nd row)	Wrench	Yes	Yes	10	M10	Force-locked	Yes	300	1
4	Remove washer & sleeve	Hand	Yes	Yes	4	$20 \times 20 \times 2$	Force-locked	Yes	2	1
5	Unstack the endplate (1st)	Hand	Yes	Yes	2640	$250 \times 180 \times 25$	-	Yes	2	2
6	Unstack insulating layer	Hand	No	No	82	$250 \times 180 \times 3$	-	Yes	2	2
7	Unstack current collector	Hand	Yes	No	220	$250 \times 180 \times 2$	-	Yes	2	2
8	Unstack flow field	Hand	Yes	Yes	18	$250 \times 180 \times 1.1$	-	Yes	2	2
9	Unstack membrane electrode assembly	Hand	No	No	98	$250 \times 180 \times 4$	-	Yes	2	2
..			repeatable steps, depends on the number of cells							
n-1	Unstack the endplate (2nd)	Hand	Yes	Yes	2640	$250 \times 180 \times 25$	-	Yes	2	2
n	Remove thread rod	Hand and hammer	Yes	Yes	280	595	plug connection	Yes	6	1

Table 6
The disassembly steps of stack 3.

Nº	Disassembly step	Required tools	Stiffness (yes/no)	Magnetic	Mass m / g	Dimensions $l \times h \times w$ / mm	Joining technology	Reversibility	Approx. Time t / s	Required number of hands
1	Disconnect interconnector from frame by breaking glass ceramic sealing	Hammer and chisel	Yes	Yes	1450	3700 × 2250	Joining by annealing	No	8	2
2	Disconnect frame from second interconnector by breaking glass ceramic sealing	Hammer and chisel	Yes	Yes	947	3700 × 2250	Joining by annealing	No	8	2
3	Breaking the porous cell out of frame	Hammer	Yes	Yes	240	200 × 200	Joining by sintering and annealing	No	5	1
4	Disconnect nickel mesh from interconnector by breaking spot welds	Hammer and chisel	Yes	Yes	-	195 × 225	Spot welding	No	>100	2
5	repetition of steps 1 to 4, depends on the number of cells									

5.1. Analysis of the disassembly steps

The described stacks were disassembled manually. The individual disassembly steps are documented in Tables 4, 5 and 6. Furthermore, the tools used for each disassembly step were specified. The disassembled parts were analyzed in terms of dimension, mass, magnetic properties, and stiffness.

5.2. Challenges in disassembly

This section gives a common and type-specific overview of meeting challenges in the disassembly of PEMFC and SOFC. The major PEMFC-specific challenges are presented in Tables 7.

The SOFC related challenges are listed in Tables 8. Both systems are sharing common challenges, which are summarized in Table 9. All challenges are classified in the respective tables according to the critical aspects regarding geometric issues, corrosion, joining techniques, and material. In general, fuel cell technology can be considered a new technology for large-scale applications. The considered fuel cells show a variety in terms of geometry, materials, and weights. This is also consistent with previous literature such as (Song et al., 2022), where a comprehensive review on assembly techniques has been carried out.

5.2.1. Selected specific challenges in disassembly of PEMFC

The mechanical analysis outlines specific challenges regarding the disassembly steps and their requirements. Therefore, certain important steps are selected and comprehensively described. Special emphasis was placed on challenges in manufacturing technology. Figure 4 shows the end plate of stack 1, where a paste partially covers the nuts. The thread-nut connection is made on both end plates to the outside. Accordingly, the paste is applied to both thread-nut connections. The paste only partially protects the nuts and seems to be eroded through the operation time.

Table 7
The PEMFC-specific challenges.

Challenge	Reference	Geometric	Corrosion	Joining	Material
Compressed stacks (extension during disassembly)	See Fig. 6			✓	✓
Limp/flexible components	See Fig. 8				✓
Higher process forces during destacking (due to adhesive-bonded sealing)	See Section 5.2.1	✓			✓
Clamping of the stack for disassembly	See Section 5.2.1	✓			

Table 8
The SOFC-specific challenges.

Challenge	Reference	Geometric	Corrosion	Joining	Material
Welded joints (e.g., nickel mesh)	See Fig. 9			✓	✓
Porous and brittle materials	See Fig. 10		✓		✓
Solid annealed sealing (entire stack baked together)	See Fig. 1			✓	✓

As shown in Fig. 5 the nuts of stack 2 are covered by plastic caps. Furthermore, every joining technology is fixed by an additional lock nut. The incomplete covering of the entire joint probably led to the corroded nuts. Consequently, two aspects have to be considered during the automated disassembly. Firstly, computer vision systems have to be capable of detecting covered nuts. Secondly, nuts and other joining techniques are subject to environmental and process influences (in terms of fuel cell: hydrogen corrosion), which may lead to different disassembly behaviors.

The fuel cell stacks are typically compressed during the assembly to achieve high energy density per square measure (Song et al., 2022). For this reason, it is expected that the compression is saved and will be converted into a length extension of stacks, compare Fig. 6. The length extension depends on the pre-load of the manufacturing process and the pre-load loss. Table 10 presents the quantitative extension of the considered PEMFC stacks. The tests also showed that single cells adhere to each other, which can subsequently lead to unexpected separation during the handling process.

An automated disassembly approach may have to consider positional changes during the disassembly process. Specifically, in case of the disassembly of nuts, strategies are required to prevent jamming of the stack (see Fig. 7), which could lead to an increasing loosening torque. Besides the disassembly of the nut itself, another important aspect is the handling of the nuts and the threaded rod.

Various sealing concepts and materials are used in PEMFC, as shown by Ye and Zhan (2013) and Stahl et al. (2015). The seal is exposed to chemical, thermal and mechanical environments. Critical parameters that accelerate seal aging can include temperature, pressure, and relative humidity. These conditions can cause the seals to bond to the substrate at the EoL of the stacks (Dillard et al., 2004). Kömmling analyses the ageing of seals. These include typical sealing materials used in PEMFC stacks. Due to chemical ageing of the seal by the critical

Table 9
The joint challenges of SOFC and PEMFC.

Challenge	Reference	Geometric	Corrosion	Joining	Material
Worn & rusted connections	See Fig. 5		✓	✓	
Different component thicknesses	See Tables 4–6	✓	✓		
Non-unified stack design	See Kampker et al. (2023)	✓			
Hazard materials (e. g., Nickel base oxide is classified as carcinogenic	See Férriz et al. (2019)				✓
Low quantity of manufactured and EoL stacks	See Clifford (2023)	✓	✓	✓	
Jamming of the different layers through tie rods	See Fig. 7	✓			
Insufficient data at disassembly step (health status, degradation, operating time)	Schiemann et al. (2007)	✓	✓	✓	✓
Difficult accessibility of joints due to small component distance	See Fig. 12	✓	✓		
Material-specific separation (e. g. degradation phenomena)	See Wu et al. (2008)		✓		✓

parameters mentioned above, chain fission reactions can occur in the polymers. These affect the macroscopic properties of the seal and cause it to become adhesive. As a result, BPP and MEA can adhere and must be separated during disassembly. Together with low component thicknesses and component distances of BPP and MEA, this poses a further challenge during disassembly. Due to the low component thicknesses, especially of the bipolar plate, there is also the challenge of clamping the stack during non-destructive disassembly without damaging the edges. In terms of material stiffness the MEA of stack 1 challenging for handling due to non-stiff flexible behavior, compare Figure 8. In Stack 2, a supporting frame holds the MEA, making handling easier.

As documented in Tables 4 and 5 both stacks have different dimensions. Due to the non-standardized market regarding fuel cell size, geometric variation can be expected during the disassembly of fuel cells.

5.2.2. *Selected specific challenges in disassembly of SOFC*

Specific challenges for disassembly have been observed with respect to SOFC. The challenges as well as requirements for the disassembly process are described as follows. A sealing is used to guarantee the tightness of the stack. The sealing prevents the mixing of the process gases. Due to the high operating temperatures and demanding conditions, the sealing must be chemically and physically stable (Sabato et al., 2016). Glass ceramic is therefore used. The solid sealing, which is firmly attached to the frame and interconnector, must be cut open during disassembly before the individual components can be destacked. Figure 9 shows the manual breaking of the sealing using a hammer and chisel. For this purpose, a force is applied to the sealing between the interconnector and the frame. In the case of automated disassembly, this requires the sealing to be detected and the tool to be precisely fed into position.

Another challenge in the disassembly of SOFC stacks is the porosity of the cell. During the operation of the stack or when the sealing is cut during disassembly, the cell can fracture. Thus, the cell frame unit can no longer be destacked as a coherent component. The broken fragments of the cell must be handled separately. A suction of smaller fragments and particles is conceivable during disassembly. Fragments and particles could also lead to a contamination of the gripper. Figure 10 shows the broken cell of a cell frame unit of the stack. Smaller fragments of the cell are still connected to the frame. Nickel meshes are used as the anode contact layer. To achieve contact between the nickel mesh and the interconnector, the meshes are spot-welded. The non-destructive separation of the nickel meshes from the interconnector poses therefore a challenge due to the many welded joints (Fig. 11). A further challenge is the difficult accessibility of joints due to small component distance (Fig. 12). This makes it difficult to insert a cutting tool and increases the risk of damage to the components during disassembly.

5.3. *Analysis of material composition*

The disassembled components have been examined for structure and composition. The SEM analysis of the cross-section of the MEA (stack 1) shows the layered structure and allows determining the thicknesses of the layer, compare Fig. 13. In the center of the MEA, the membrane (30–50 μm) can be seen, which is coated with the electrodes (∼10 μm and ∼19 μm, respectively). The elements C, O, F and S are indicated by determining the composition with an EDS analysis, which can be assigned to the membrane material perfluorosulfonic acid (PFSA). According to the literature (Kurzweil, 2012), it is the most commonly used material for membranes, e.g., under the brand name Nafion.

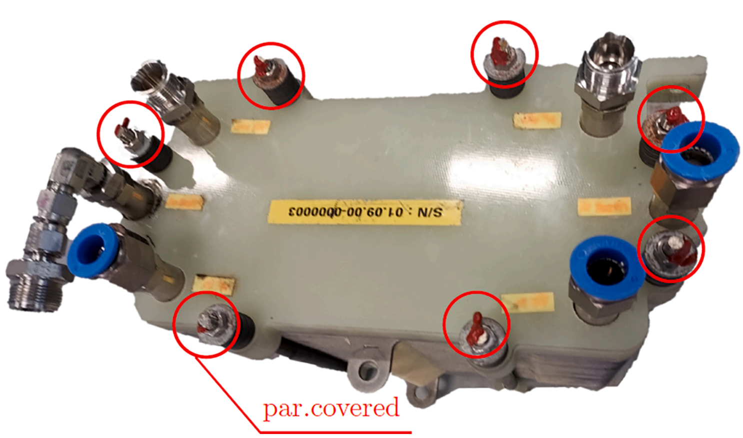


Fig. 4. The partially covered nuts of stack 1.

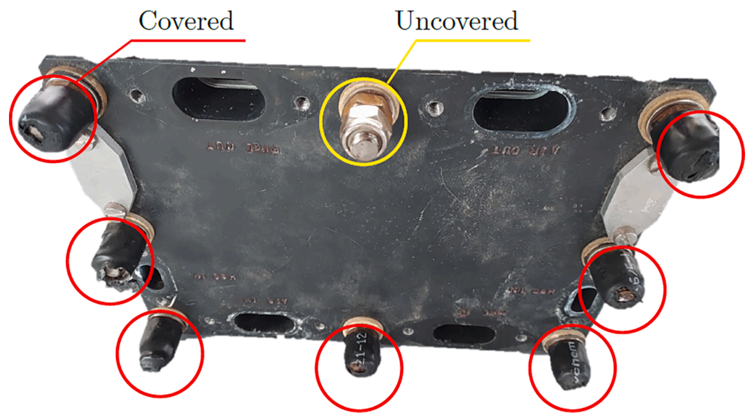


Fig. 5. The covered nuts at stack 2.

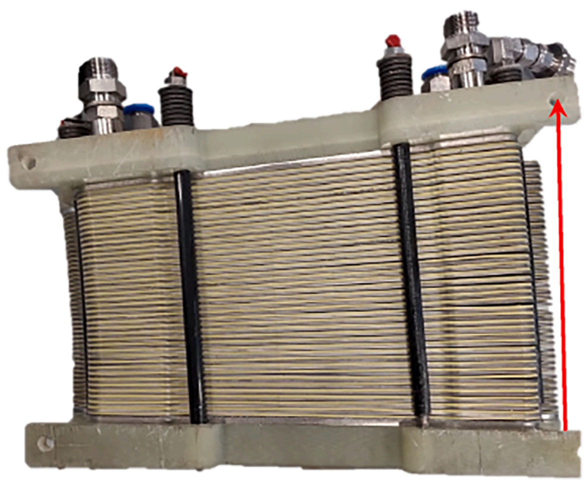


Fig. 6. The length extension on the right-hand side of stack 1 while unfastening the nuts.

Table 10
The quantitative extension of the stacks.

Stack	Original length l_o / mm	Extended length l_{ex} / mm	Increase i_{ex} / %
Stack 1	164	177	7.93
Stack 2	570	577	1.22

For a composition analysis of the electrodes, the GDL had to be removed manually. Then the revealed surface could be analyzed by EDS. The results show that one electrode uses only platinum as a catalyst, whereas the other side also contains ruthenium. In comparison with the literature (Auer et al., 1998; Kurzweil, 2012), the side containing ruthenium can be assigned to the fuel gas electrode (anode), since ruthenium is used to prevent CO poisoning of the catalyst. GDLs are applied to both sides of the electrodes (~250 μm and ~220 μm, respectively), whereby a microporous layer (MPL) can also be seen towards the electrode. EDS analysis shows that the carbon fibers of the GDL are treated with polytetrafluoroethylene (PTFE).

The MEA of stack 2 has the same structure as the one just described. Differences can only be found in the composition of the electrodes. The electrodes do not contain ruthenium as a catalyst, instead both electrodes use only platinum as a catalyst according to EDS analysis. This makes an identification of the electrodes not possible.

Furthermore, the composition of the flow fields was determined by EDS. Both are made of a metal foam, whereby one consists mainly of nickel and has a core of aluminum. The other consists mainly of chromium. In the literature, nickel is reported chiefly as the material for metal foam flow fields (Kim et al., 2018). The analysis of the other components with the FT-IR measurement showed that the bipolar plates of both stacks were made of stainless steel with the alloy elements chrome, nickel, and molybdenum. Especially the bipolar plate of stack 2 is similar in composition to the frequently used stainless steel 316, which is mentioned in the literature as a material for bipolar plates (Xiao Zi et al., 2005). The end plate of stack 1 is made of a phenolic resin; the end plate of stack 2 has an aluminum core coated with zinc.

Fig. 7. Unstacking the PEMFC Stack.

5.4. Prospects on automated disassembly concept

Several aspects have been taken into account regarding automated disassembly. Based on the manual disassembly experiments, process routes and a morphological box has been developed for the future design of the automatic cell. Table 11 presents the proposed concept (with two possible solutions) of the automated disassembly. Due to the low

Fig. 8. The flexible behavior of Stack 1.

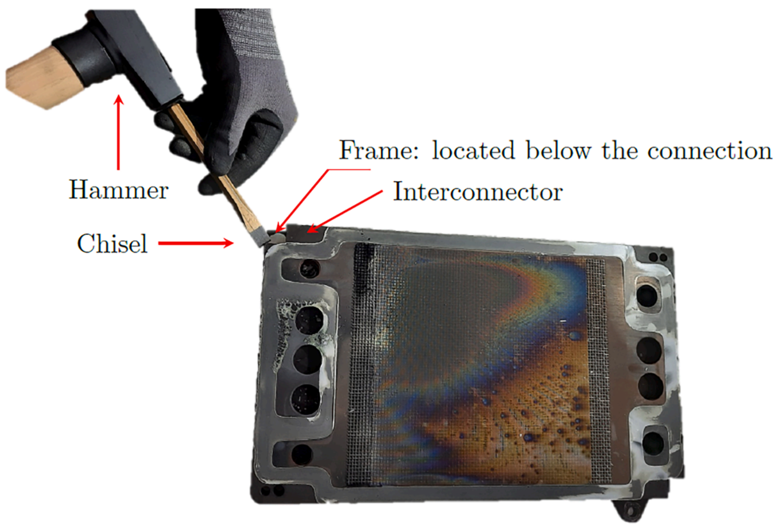


Fig. 9. Breaking the glass ceramic sealant (SOFC Stack from Forschungszentrum Jülich).

expected and practical found weight, a lightweight robot (up to 10 kg) can be used for the disassembly process. Also the weight of the tools, Human-Robot-Collaboration should consider that carcinogenic materials are used in fuel cells. Therefore, an exhaust system is suggested to reduce Aerosol. The number of robots can be limited to one robot by utilizing external fixation devices in case of screw/nut spinning. Articulated robots offer flexibility in terms of different geometric and process-specific requirements. The different sizes of end plates/fuel cell stacks require flexibility in placing and the subsequent fixation. T-slot and hole pattern work tables provide this flexibility. A manual feed process is suggested based on the current low expected lot size. Although pneumatic screwdrivers are inexpensive to purchase, they are not economical due to energy losses during operation. However, in manual disassembly, they are used to dissemble fasteners. The handling can be conducted by using one or two gripper principles e.g., magnetic/clamping for the magnetic components. However, our manual disassembly also showed non-magnetic components. Therefore, a second gripper principle, such as suction, is suggested to deal with different requirements. The compensation of positional errors and force-sensitive disassembly could be realized using a force control approach. In the case of disassembly for non-remanufacturing purposes, the position control of the robot is sufficient.

The disassembly process routes of PEMFC and SOFC stacks were developed based on the stack designs of the stacks investigated in this work. In Fig. 14a and b, respectively, the process routes are presented. No specific separation methods are specified here. However, possible specific separation methods are given in the following section with reference to DIN 8580 and DIN/TS 54405 (DIN8580, 2020; DIN/TS54405, 2020). The aim of disassembly is to achieve the most material-specific separation of the process input possible.

For the process route of PEMFC stacks an entire PEMFC stack without BoP components is considered as process input. The first step is to disassemble the tensioning system. This process step requires the stack to be compressed because a mechanical stress of several kN is applied to the stack. The tensioning system can be disassembled by unscrewing (3.5.3.1 - DIN8580) the nuts and extracting (3.5.1.4 - DIN8580) the tie rods. Nuts and possibly existing disc springs as well as tie rods are sorted and stored separately. The compression can be released afterwards. Depending on the degree of degradation of the tie rods with regard to corrosion, it may be necessary to extracting the tie rods only after the cell units have been destacked, since they cannot be extracted beforehand. Depending on the stack design and concept of the tensioning system, for example tensioning bands instead of tie rods, other cutting methods such as 3.1.1 Shear cutting, 3.1.2 Knife cutting or 3.2 Machining with geometrically determined cutting edges according to DIN 8580 must be used. Depending on the stack design and other influencing factors still to be investigated, the individual components of the cell units BPP and MEA can adhere to each other at the end-of-life of a stack. This influences the destacking of these components. There are two scenarios that can be adopted. In scenario 1, the components adhere to each other only marginally. This allows BPP and MEA to be destacked while the top component is gripped and the lower components or the remaining stack are fixed. In scenario 2, the components adhere strongly to each other. This makes a separation process mandatory. Possible separation processes for this are processes according to DIN/TS 54405. Since the MEA is a composite of different subcomponents and materials, this composite has to be further disassembled into GDL, CCM and Sealing by applying additional separation processes. In Fig. 14b an

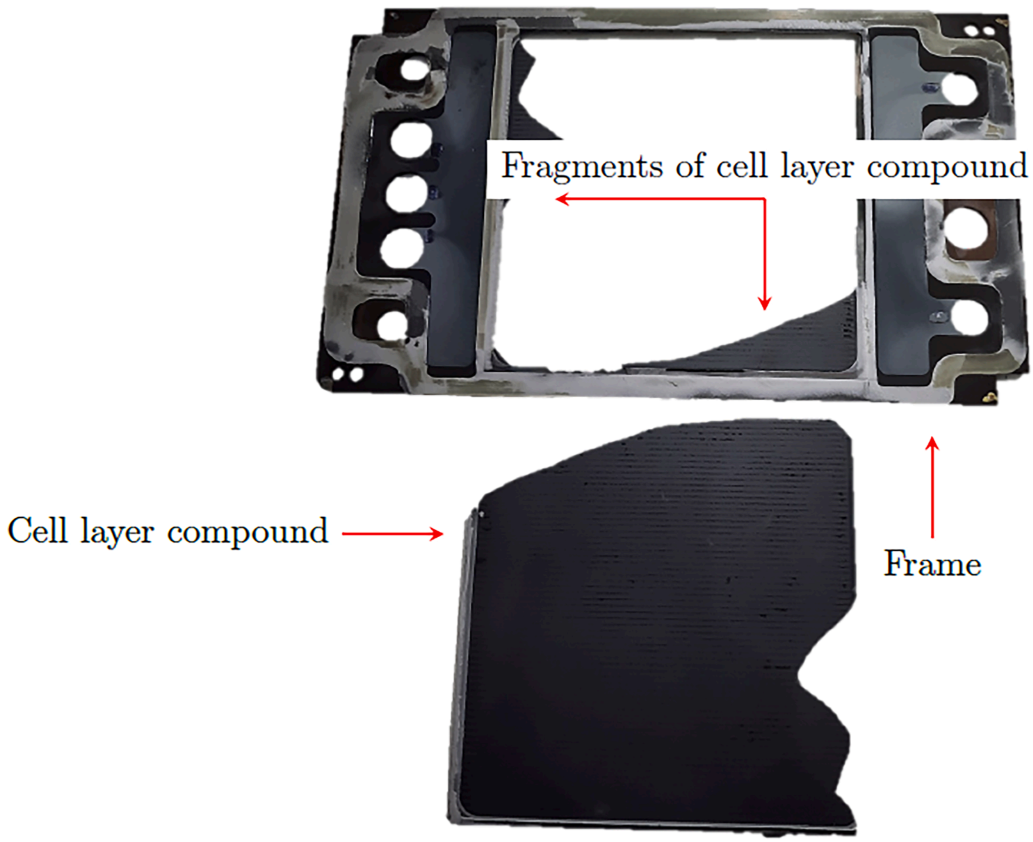


Fig. 10. Broken cell layer compound of a repeat unit of SOFC Stack (SOFC Stack from Forschungszentrum Jülich).

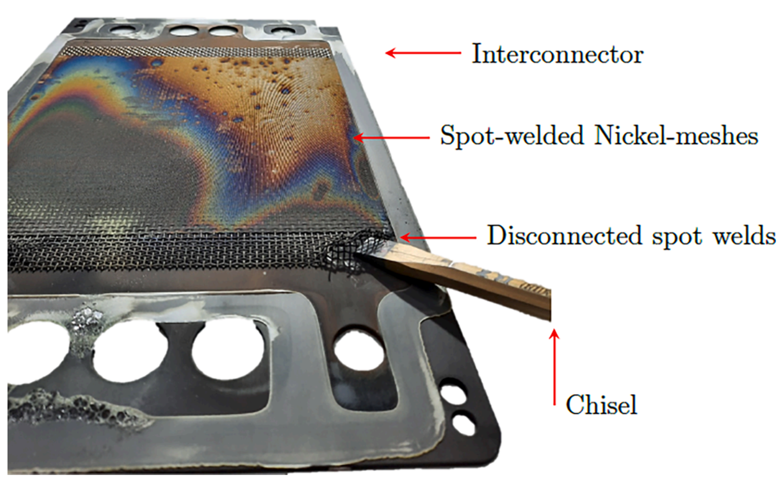


Fig. 11. Disconnecting the spot welds of the nickel mesh (SOFC Stack from Forschungszentrum Jülich).

entire SOFC stack without BoP as process input is also considered. The disassembly of the tensioning system can be applied analogously to PEMFC. Differences occur during the destacking of the stack: Due to the solid sealing material in SOFC stacks, a separation step is mandatory. In this case, the joining connection must be broken. During this separation step, fragments of the brittle sealing may occur. These need to be suctioned off (3.6.3.3 - DIN 8580). While separating the interconnector and the cell frame unit by breaking the sealing, cracks and even fractures may occur in the cell due to its brittle properties. The fragments of the cell must be removed separately during disassembly, as they are highly relevant for further recycling due to the rare earths they contain. Similar to the MEA of the PEMFC stack, the cell frame unit consists of various subcomponents. This composite must be further subdivided into material-specific components by means of further separation processes. This also applies to the composite of interconnector and nickel mesh, which is joined by spot welding.

6. Discussion

The aspect of corroded joining technologies such as screws in the disassembly of fuel cells corresponds with previous works of Apley et al., Büker et al., Harper et al., which considered the disassembly of electronic devices, battery systems from automotive applications, and wheels of cars. Besides the environmental influence on the joining

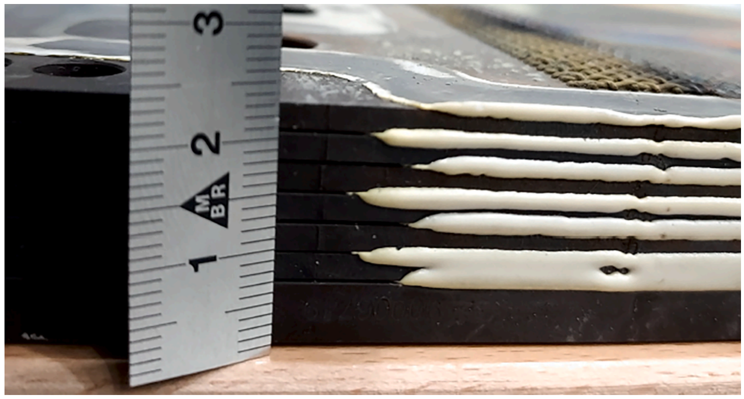


Fig. 12. Small component distance (SOFC Stack from Forschungszentrum Jülich).

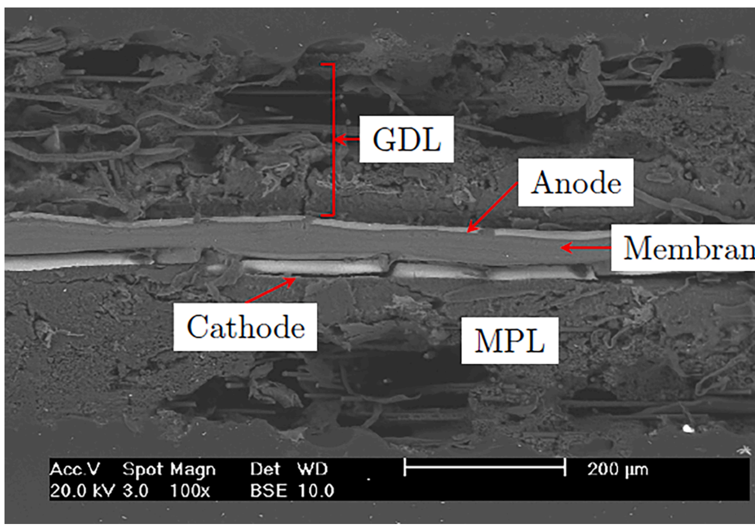


Fig. 13. Cross section of MEA of stack 1.

Table 11
The developed morphological box (including solution 1 — and solution 2 —) for an automated disassembly of fuel cell stacks.

Part	Alternatives				
System	Human-Robot-Collaboration	Lightweight robot	Industrial robot		
Number of robots	1	2	3		
Robot type	Articulated robots	SCARA	Portal robot	Delta robot	Cable robot
Work table	Standard	T-Slot	Hole pattern		
Feeding	Assembly line	Roll conveyors	Manual		
Screw driver	Electric	Pneumatic			
Gripper	Magnetic line	Vacuum suction	Clamping gripper	Finger gripper	
Sensors	Force-Torque	Visual	Position		

technology, it should be considered that the interacting media inside fuel cell stacks (hydrogen, oxygen, and water) favor a corrosive behavior in case of leakage.

The considered fuel cell stacks do not include new designs such as (Bosch GmbH, 2022), where additional strapping is used to tighten the entire stack. This means that additional disassembly steps and processes have to be considered. Furthermore, individual cells or components such as seals can attach to each other at the end-of-life of the stacks, which requires an additional separation process. The analysis of the factors influencing adhesion and the development of suitable separation processes must be considered in the future. It is also necessary to investigate how individual components such as the MEA or the cell frame unit can be further mechanically separated on a material-specific basis. Since disassembly is only the first step in realizing a circular economy for fuel cells, further recycling steps up to material recovery and other circular economy strategies such as reuse or remanufacturing of components must be researched.

The gained information based on manual experiments, composition

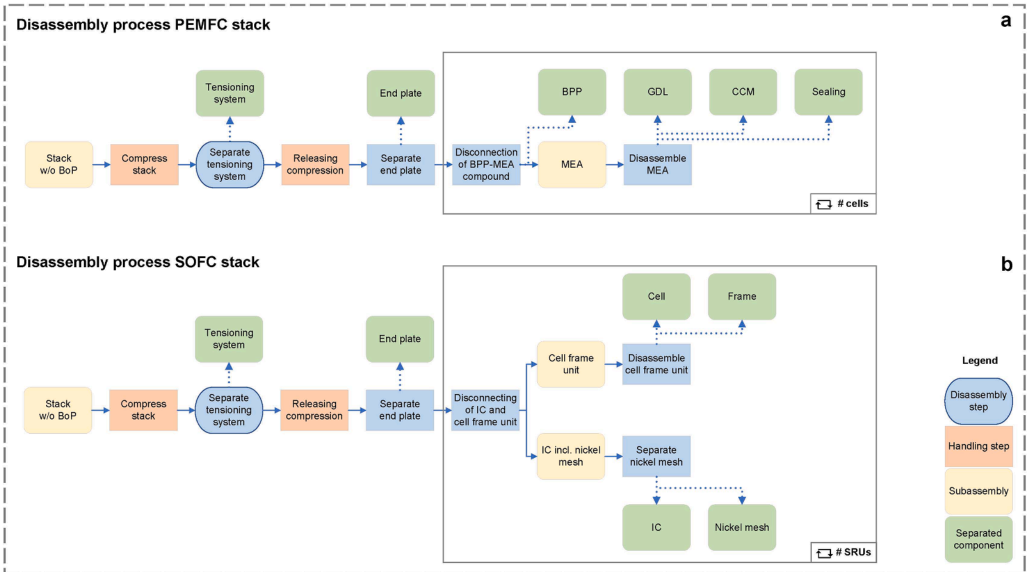


Fig. 14. Disassembly process of PEMFC stack (a) and disassembly process of SOFC stack (b).

analysis and the automation concept serves as basis for product improvements in terms of design for disassembly, which could accelerate future disassembly of fuel cell stacks. Due to non-existent standardization, the stack structure and material composition vary depending on the stack and component design.

7. Conclusions and future work

The present research aimed to examine the challenges and prospects of automated disassembly of fuel cells for a circular economy. Therefore, manual disassembly experiments have been carried out using three samples. A material analysis has been conducted to underline the significance of the circular economy approaches. Furthermore, from there, the following essential aspects can be derived:

- A small lot size and quantity makes the automated disassembly of fuel cells challenging in terms of technological and economical aspects.
- An automated disassembly of fuel cells should take into account combination between destructive and non-destructive methods.
- High system flexibility is required in terms of sizes, payloads, material property and product state.
- A robot-based cell serves as flexible solution for the disassembly of the stacks, specific aspects could be handled by external peripheral devices.
- From the material perspective, the catalyst (in our dissembled samples consisting of platinum) is the most valuable fuel cell material and should be recovered in a high rate.

Future works should investigate a further material-specific separation of the disassembled components. Therefore, the separation of the MEA of the PEMFC as well as the composite of interconnector and nickel mesh and the composite of frame and cell of the SOFC should be considered and automated processes must be developed. For disconnecting the spot welds of the nickel mesh, laser-based technology such as laser cutting should be considered. Closing the cycle requires a subsequent classification of the disassembled components with regard to their suitability for reuse, remanufacturing or recycling. In general, a comparison of disassembly time, per-unit disassembly costs, and overall equipment investment costs between manual disassembly and manual disassembly must be made. Finally, technologies for the above-mentioned paths must be developed for the individual components and materials.

CRediT authorship contribution statement

Anwar Al Assadi: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Dominik Goes:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Sabri Baazouzi:** Conceptualization, Writing – original draft. **Malena Staudacher:** Conceptualization, Investigation, Methodology, Writing – original draft. **Piotr Malczyk:** Investigation, Resources. **Werner Kraus:** Funding acquisition, Resources, Writing – review & editing. **Frank Nägele:** Writing – review & editing. **Marco F. Huber:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Jürgen Fleischer:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Urs Peuker:** Funding acquisition, Project administration, Resources. **Kai Peter Birke:** Funding acquisition, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge the financial support by the German Federal Ministry of Education and Research (BMBF) within the project "ReNaRe – Recycling – Nachhaltige Ressourcennutzung" under grant numbers 03HY111A-C. The authors would also like to thank the colleagues from the German Aerospace Center (DLR), Stuttgart and the Forschungszentrum Jülich for their material support. The authors would also like to thank Matthias Lempa for the support during the experimental phase of this work.

References

Abbasi, T., Abbasi, S.A., 2011. 'Renewable' hydrogen: prospects and challenges. Renew. Sustain. Energy Rev. 15 (6), 3034–3040.
Alfaro-Algaba, M., Ramirez, F.J., 2020. Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing. Resour. Conserv. Recycl. 154, 104461.
Apley, D.W., Seliger, G., Voit, L., Shi, J., 1998. Diagnostics in disassembly unscrewing operations. Int. J. Flexible Manuf. Syst. 10 (2), 111–128.
Auer, E. D., Freund, A. D., Lehmann, T. D., Starz, K.-a. D., Schwarz, R. D., Stenke, U. D., 1998. Co-tolerant anode catalyst for PEM fuel cell and its method of manufacturing.
Baazouzi, S., Rist, F.P., Weeber, M., Birke, K.P., 2021. Optimization of disassembly strategies for electric vehicle batteries. Batteries.
Bdiwi, M., Rashid, A., Putz, M., 2016. Autonomous disassembly of electric vehicle motors based on robot cognition. 2016 IEEE International Conference on Robotics and Automation (ICRA). IEEE, pp. 2500–2505.
Bernard, J., Delprat, S., Buchi, F.N., Guerra, T.M., 2009. Fuel-cell hybrid powertrain: toward minimization of hydrogen consumption. IEEE Trans. Veh. Technol. 58 (7), 3168–3176.
Bobba, S., Carrara, S., Huisman, J., Mathieux, F., Pavel, C., 2020. Critical raw materials for strategic technologies and sectors in the EU - a foresight study. 10.2873/58081.
Bosio, B., Bianchi, F.R., 2023. Multiscale modelling potentialities for solid oxide fuel cell performance and degradation analysis. Sustain. Energy Fuels 7 (1), 280–293.
Büker, U., Drüe, S., Götze, N., Hartmann, G., Kalkreuter, B., Stemmer, R., Trapp, R., 2001. Vision-based control of an autonomous disassembly station. Rob. Autonomous Syst. 35 (3), 179–189. https://doi.org/10.1016/S0921-8890(01)00121-X.Seventh Symposium on Intelligent Robotic Systems - SIRS'99
Choux, M., Marti Bigorra, E., Tyapin, I., 2021. Task planner for robotic disassembly of electric vehicle battery pack. Metals 11 (3), 387.
Clifford, J., 2023. Toyota ramps up production to meet expected ten-fold growth in hydrogen fuel cell vehicles. https://mag.toyota.co.uk/toyota-ramps-up-product ion-to-meet-expected-ten-fold-growth-in-hydrogen-fuel-cell-vehicles/. Accessed: 2023-03-28.
DiFilippo, N.M., Jouaneh, M.K., 2017. A system combining force and vision sensing for automated screw removal on laptops. IEEE Trans. Autom. Sci. Eng. 15 (2), 887–895.
Dillard, D., Guo, S., Ellis, M., Lesko, J., Dillard, J., Sayre, J., Vijayendran, B., 2004. Seals and sealants in PEM fuel cell environments: material, design, and durability challenges. https://doi.org/10.1115/FUELCELL2004-2520.
DIN8580, 2020. Manufacturing processes - terms and definitions, division.
DIN/TS54405, 2020. Construction adhesives – guideline for separation and recycling of adhesives and substrates from bonded joints.
Edwards, P.P., Kuznetsov, V.L., David, W.I.F., Brandon, N.P., 2008. Hydrogen and fuel cells: Towards a sustainable energy future. Energy Policy 36 (12), 4356–4362. https://doi.org/10.1016/j.enpol.2008.09.036.Foresight Sustainable Energy Management and the Built Environment Project
Feldmann, K., Trautner, S., Meedt, O., 1999. Innovative disassembly strategies based on flexible partial destructive tools. Annu. Rev. Control 23, 159–164.
Fergus, J.W., 2005. Sealants for solid oxide fuel cells. J. Power Sources 147 (1), 46–57. https://doi.org/10.1016/j.jpowsour.2005.05.002.
Férriz, A.M., Bernad, A., Mori, M., Fiorot, S., 2019. End-of-life of fuel cell and hydrogen products: a state of the art. Int. J. Hydrogen Energy 44 (25), 12872–12879. https://doi.org/10.1016/j.ijhydene.2018.09.176.Special Issue on Selected Contributions from the European Hydrogen Energy Conference 2018. Málaga, Spain. March 14th - 16th
Gerbers, R., Mücke, M., Dietrich, F., Dröder, K., 2016. Simplifying robot tools by taking advantage of sensor integration in human collaboration robots. Procedia CIRP 44, 287–292.
Gerbers, R., Wegener, K., Dietrich, F., Dröder, K., 2018. Safe, flexible and productive human-robot-collaboration for disassembly of lithium-ion batteries. Recycling of Lithium-Ion Batteries: The Lithorec Way, pp. 99–126.
Glöser-Chahoud, S., Huster, S., Rosenberg, S., Baazouzi, S., Kiemel, S., Singh, S., Schneider, C., Weeber, M., Miehe, R., Schultmann, F., 2021. Industrial disassembling as a key enabler of circular economy solutions for obsolete electric vehicle battery systems. Resour. Conserv. Recycl. 174, 105735.
Go, T.F., Wahab, D.A., Rahman, M.N.A., Ramli, R., Hussain, A., 2012. Genetically optimised disassembly sequence for automotive component reuse. Expert Syst. Appl. 39 (5), 5409–5417.
Gungor, A., Gupta, S.M., 1998. Disassembly sequence planning for products with defective parts in product recovery. Comput. Ind. Eng. 35 (1-2), 161–164.
Harboe, S., Schreiber, A., Margaritis, N., Blum, L., Guillon, O., Menzler, N.H., 2020. Manufacturing cost model for planar 5 kWel SOFC stacks at Forschungszentrum Jülich. Int. J. Hydrogen Energy 45 (15), 8015–8030. https://doi.org/10.1016/j.ijhydene.2020.01.082.
Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., et al., 2019. Recycling lithium-ion batteries from electric vehicles. Nature 575 (7781), 75–86.
Hjorth, S., Chrysostomou, D., 2022. Human–robot collaboration in industrial environments: a literature review on non-destructive disassembly. Rob. Comput.-Integr. Manuf. 73, 102208.
Hohm, K., Hofstede, H.M., Tolle, H., 2000. Robot assisted disassembly of electronic devices. Proceedings. 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000)(Cat. No. 00CH37113), Vol. 2. IEEE, pp. 1273–1278.
Huang, J., Pham, D.T., Wang, Y., Qu, M., Ji, C., Su, S., Xu, W., Liu, Q., Zhou, Z., 2020. A case study in human–robot collaboration in the disassembly of press-fitted components. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 234 (3), 654–664.
Husar, A., Serra, M., Kunusch, C., 2007. Description of gasket failure in a 7 cell PEMFC stack. J. Power Sources 169 (1), 85–91. https://doi.org/10.1016/j.jpowsour.2007.01.078.CONAPPICE 2006
Jin, X., 2016. A review on end-of-life battery management: challenges, modeling, and solution methods. Adv. Battery Manuf. Serv. Manage. Syst. 79.
Kampker, A., Heimes, H., Kehrer, M., Hagedorn, S., Reims, P., Kaul, O., 2023. Fuel cell system production cost modeling and analysis. Energy Rep. 9, 248–255.
Karlsson, B., Järrhed, J.-O., 2000. Recycling of electrical motors by automatic disassembly. Meas. Sci. Technol. 11 (4), 350.
Ke, Q., Zhang, P., Zhang, L., Song, S., 2020. Electric vehicle battery disassembly sequence planning based on frame-subgroup structure combined with genetic algorithm. Front. Mech. Eng. 102.
Kennouche, D., Fang, Q., Blum, L., Stolten, D., 2018. Analysis of the cathode electrical contact in SOFC stacks. J. Electrochem. Soc. 165 (9), F677–F683. https://doi.org/10.1149/2.0761809jes.
Kim, J.S., Park, J.B., Kim, Y.M., Ahn, S.-H., Sun, H.Y., Kim, K.H., 2008. Fuel cell end plates: A review. Int. J. Precis. Eng. Manuf. 9, 33–46.
Kim, M., Kim, C., Sohn, Y., 2018. Application of metal foam as a flow field for PEM fuel cell stack. Fuel Cells 18 (2), 123–128. https://doi.org/10.1002/fuce.201700180.
Klas, C., Hundhausen, F., Gao, J., Dreher, C.R.G., Reither, S., Zhou, Y., Asfour, T., 2021. The KIT gripper: a multi-functional gripper for disassembly tasks. 2021 IEEE International Conference on Robotics and Automation (ICRA). IEEE, pp. 715–721.
Knackfuss, P., Schmidt, A., 1996. Application of an optical 3D sensor for automated disassembling. Rapid Prototyping, Vol. 2787. SPIE, pp. 97–102.
Knoth, R., Brandstotter, M., Kopacek, B., Kopacek, P., 2002. Automated disassembly of electr(on)ic equipment. Conference Record 2002 IEEE International Symposium on Electronics and the Environment (Cat. No. 02CH37273). IEEE, pp. 290–294.
Kömmling, A., 2017. Alterung und lebensdauervorhersage von o-ring-dichtungen.
Kroll, E., Beardsley, B., Parulian, A., 1996. A methodology to evaluate ease of disassembly for product recycling. IIE Trans. 28 (10), 837–846.
Kurzweil, P., 2012. Brennstoffzellentechnik: Grundlagen, Komponenten, Systeme, Anwendungen. SpringerLink : Bücher, Springer Fachmedien Wiesbaden.https://books.google.de/books?id=uumBU582uXMC
Laili, Y., Li, Y., Fang, Y., Pham, D.T., Zhang, L., 2020. Model review and algorithm comparison on multi-objective disassembly line balancing. J. Manuf. Syst. 56, 484–500.
Lajunen, A., Sainio, P., Laurila, L., Pippuri-Mäkeläinen, J., Tammi, K., 2018. Overview of powertrain electrification and future scenarios for non-road mobile machinery. Energies 11 (5), 1184.
Lander, L., Cleaver, T., Rajaeifar, M.A., Nguyen-Tien, V., Elliott, R.J.R., Heidrich, O., Kendrick, E., Edge, J.S., Offer, G., 2021. Financial viability of electric vehicle lithium-ion battery recycling. Iscience 24 (7), 102787.
Li, R., Pham, D.T., Huang, J., Tan, Y., Qu, M., Wang, Y., Kerin, M., Jiang, K., Su, S., Ji, C., Liu, Q., Zhou, Z., 2020. Unfastening of hexagonal headed screws by a collaborative robot. IEEE Trans. Autom. Sci. Eng. 17 (3), 1455–1468. https://doi.org/10.1109/TASE.2019.2958712.
Li, X., Kuang, X., Sun, J., 2020. Rare earth elements based oxide ion conductors. Inorg. Chem. Front. 8 https://doi.org/10.1039/D0QI00848F.
Liu, B., Wei, M.Y., Ma, G.J., Zhang, W., Wu, C.W., 2016. Stepwise optimization of endplate of fuel cell stack assembled by steel belts. Int. J. Hydrogen Energy 41 (4), 2911–2918. https://doi.org/10.1016/j.ijhydene.2015.12.047.
Ma, L., Zimmerer, N., Schäfer, J., Quarz, P., Heckmann, T., Scharfer, P., Schabel, W., Fleischer, J., 2022. Investigation on a micro-environment concept for MEA production process supported by numerical simulations. FC Fuel Cell Conference Chemnitz, KONFERENZBAND, p. 209.
Manoharan, Y., Hosseini, S.E., Butler, B., Alzhahrani, H., Senior, B.T.F., Ashuri, T., Krohn, J., 2019. Hydrogen fuel cell vehicles; current status and future prospect. Appl. Sci. 9 (11), 2296.
Maric, R., Mirshekari, G., 2021. Solid Oxide Fuel Cells: From Fundamental Principles to Complete Systems. Electrochemical Energy Storage & conversion. CRC Press/Taylor & Francis Group, LLC.https://books.google.de/books?id=WokAzgEACAAJ
Marshall, J., Gastol, D., Sommerville, R., Middleton, B., Goodship, V., Kendrick, E., 2020. Disassembly of Li Ion cell–characterization and safety considerations of a recycling scheme. Metals 10 (6). https://doi.org/10.3390/met10060773.
Meng, K., Xu, G., Peng, X., Youcef-Toumi, K., Li, J., 2022. Intelligent disassembly of electric-vehicle batteries: a forward-looking overview. Resour. Conserv. Recycl. 182, 106207.
Robert Bosch GmbH, R.B., 2022. Fuel-cell stacks: the recipe for success in mass manufacturing. https://www.bosch.com/stories/fuel-cell-stack/. Accessed: 2021-02-11.
Nave, M., 2003. Beitrag zur automatisierten demontage durch optimierung des trennprozesses von schraubenverbindungen.
Olabi, A.G., Wilberforce, T., Sayed, E.T., Elsaid, K., Abdelkareem, M.A., 2020. Prospects of fuel cell combined heat and power systems. Energies 13 (16). https://doi.org/10.3390/en13164104.
O'Shea, B., Grewal, S.S., Kaebernick, H., 1998. State of the art literature survey on disassembly planning. Concurrent Eng. 6 (4), 345–357.
Poschmann, H., Brueggemann, H., Goldmann, D., 2020. Disassembly 4.0: a review on using robotics in disassembly tasks as a way of automation. Chemie Ingenieur Technik 92 (4), 341–359.
Potting, J., Hekkert, M.P., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain. PBL publishers.
Rallo, H., Benveniste, G., Gestoso, I., Amante, B., 2020. Economic analysis of the disassembling activities to the reuse of electric vehicles Li-Ion batteries. Resour. Conserv. Recycl. 159, 104785.

Rashapov, R., Unno, J., Gostick, J., 2015. Characterization of PEMFC gas diffusion layer porosity. J. Electrochem. Soc. 162, F603–F612. https://doi.org/10.1149/2.0921506jes.

Rastegarpanah, A., Ner, R., Stolkin, R., Marturi, N., 2021. Nut unfastening by robotic surface exploration. Robotics 10 (3), 107.

Ren, Y., Jin, H., Zhao, F., Qu, T., Meng, L., Zhang, C., Zhang, B., Wang, G., Sutherland, J. W., 2020. A multiobjective disassembly planning for value recovery and energy conservation from end-of-life products. IEEE Trans. Autom. Sci. Eng. 18 (2), 791–803.

Ren, Y., Tian, G., Zhao, F., Yu, D., Zhang, C., 2017. Selective cooperative disassembly planning based on multi-objective discrete artificial bee colony algorithm. Eng. Appl. Artif. Intell. 64, 415–431.

Ren, Y., Zhang, C., Zhao, F., Xiao, H., Tian, G., 2018. An asynchronous parallel disassembly planning based on genetic algorithm. Eur. J. Oper. Res. 269 (2), 647–660.

Rosenberg, S., Huster, S., Baazouzi, S., Glöser-Chahoud, S., Al Assadi, A., Schultmann, F., 2022. Field study and multimethod analysis of an EV battery system disassembly. Energies 15 (15), 5324.

Sabato, A.G., Cempura, G., Montinaro, D., Chrysanthou, A., Salvo, M., Bernardo, E., Secco, M., Smeacetto, F., 2016. Glass-ceramic sealant for solid oxide fuel cells application: characterization and performance in dual atmosphere. J. Power Sources 328, 262–270. https://doi.org/10.1016/j.jpowsour.2016.08.010.

Sakai, N., Yamaji, K., Horita, T., Xiong, Y.P., Yokokawa, H., 2005. Chapter 223 - Rare-Earth Materials for Solid Oxide Fuel Cells (SOFC). In: Handbook on the Physics and Chemistry of Rare Earths, Vol. 35. Elsevier, pp. 1–43. https://doi.org/10.1016/S0168-1273(05)35001-X.

Sarner, S., Schreiber, A., Menzler, N.H., Guillon, O., 2022. Recycling strategies for solid oxide cells. Adv. Energy Mater. 12 (35), 2201805.

Schiemann, J., Kerßenboom, A., Prause, H.J., Peil, S., 2007. Handbuch Verwertung von Brennstoffzellen und deren Peripherie-Systeme. Institut für Energie-und Umwelttechnik eV: Duisburg, Germany.

Schmitt, J., Haupt, H., Kurrat, M., Raatz, A., 2011. Disassembly automation for lithium-ion battery systems using a flexible gripper. 2011 15th International Conference on Advanced Robotics (ICAR). IEEE, pp. 291–297.

Scholz-Reiter, B., Scharke, H., Hucht, A., 1999. Flexible robot-based disassembly cell for obsolete TV-sets and monitors. Rob. Comput.-Integr. Manuf. 15 (3), 247–255.

Schäfer, J., Allmendinger, S., Hofmann, J., Fleischer, J., 2021. Genetic algorithm for the optimization of vision acquisition for on-the-fly position measurement of individual layers in fuel cell stack assembly. Procedia CIRP 104, 1407–1411. https://doi.org/10.1016/j.procir.2021.11.237.54th CIRP CMS 2021 - Towards Digitalized Manufacturing 4.0

Seliger, G., Keil, T., Rebafka, U., Stenzel, A., 2001. Flexible disassembly tools. Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment. 2001 IEEE ISEE (Cat. No. 01CH37190). IEEE, pp. 30–35.

Song, K., Wang, Y., Ding, Y., Xu, H., Mueller-Welt, P., Stuermlinger, T., Bause, K., Ehrmann, C., Weinmann, H.W., Schaefer, J., Fleischer, J., Zhu, K., Weihard, F., Trostmann, M., Schwartze, M., Albers, A., 2022. Assembly techniques for proton exchange membrane fuel cell stack: a literature review. Renew. Sustain. Energy Rev. 153, 111777. https://doi.org/10.1016/j.rser.2021.111777.

Stahl, P., Biesdorf, J., Boillat, P., Kraft, J., Friedrich, K.A., 2015. Water distribution analysis in the outer perimeter region of technical PEFC based on neutron radiography. J. Electrochem. Soc. 162 (7), F677. https://doi.org/10.1149/2.0351507jes.

Stambouli, A., Traversa, E., 2002. Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy. Renew. Sustain. Energy Rev. 6, 433–455. https://doi.org/10.1016/S1364-0321(02)00014-X.

Steele, B.C.H., Heinzel, A., 2011. Materials for fuel-cell technologies. Materials for Sustainable Energy: A Collection of Peer-Reviewed Research and Review Articles from Nature Publishing Group. World Scientific, pp. 224–231.

Taherian, R., 2014. A review of composite and metallic bipolar plates in proton exchange membrane fuel cell: materials, fabrication, and material selection. J. Power Sources 265, 370–390. https://doi.org/10.1016/j.jpowsour.2014.04.081.

Töpler, J., Lehmann, J.,. Wasserstoff und Brennstoffzelle: Technologien und Marktperspektiven.

Uchiyama, Y., Fujisawa, R., Oda, Y., Hirasawa, E., 1999. Air conditioner and washing machine primary disassembly process. Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, pp. 258–262.

US Department of Energy, 2023. Fuel cells. https://www.energy.gov/eere/fuelcells/fuel-cells. Accessed: 2023-03-28.

VDI2221, 2019. Vdi 2221, design of technical products and systems model of product design.

Vongbunyong, S., Chen, W.H., Vongbunyong, S., Chen, W.H., 2015. Disassembly Automation. Springer.

Waldmann, T., Iturrondobeitia, A., Kasper, M., Ghanbari, N., Aguesse, F., Bekaert, E., Daniel, L., Genies, S., Gordon, I.J., Löble, M.W., Vito, E.D., Wohlfahrt-Mehrens, M., 2016. Review - post-mortem analysis of aged lithium-ion batteries: Disassembly methodology and physico-chemical analysis techniques. J. Electrochem. Soc. 163 (10), A2149–A2164. https://doi.org/10.1149/2.1211609jes.

Wegener, K., Chen, W.H., Dietrich, F., Dröder, K., Kara, S., 2015. Robot assisted disassembly for the recycling of electric vehicle batteries. Procedia Cirp 29, 716–721.

Weyrich, M., Wang, Y., 2013. Architecture design of a vision-based intelligent system for automated disassembly of e-waste with a case study of traction batteries. 2013 IEEE 18th Conference on Emerging Technologies & Factory Automation (ETFA). IEEE, pp. 1–8.

Wittstock, R., Pehlken, A., Wark, M., 2016. Challenges in automotive fuel cells recycling. Recycling 1 (3), 343–364.

Wu, J., Liu, X., 2010. Recent development of SOFC metallic interconnect. J. Mater. Sci. Technol. 26 (4), 293–305. https://doi.org/10.1016/S1005-0302(10)60049-7.

Wu, J., Yuan, X.Z., Martin, J.J., Wang, H., Zhang, J., Shen, J., Wu, S., Merida, W., 2008. A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies. J. Power Sources 184 (1), 104–119. https://doi.org/10.1016/j.jpowsour.2008.06.006.

Wu, T., Zhang, Z., Yin, T., Zhang, Y., 2022. Multi-objective optimisation for cell-level disassembly of waste power battery modules in human-machine hybrid mode. Waste Manage. 144, 513–526.

Xiao Zi, Y., Haijiang Wang, J.Z., Wilkinson, D.P., 2005. Bipolar plates for PEM fuel cells - from materials to processing. J. New Mater. Electrochem. Syst. 8, 257–267.

Ye, D.-h., Zhan, Z.-g., 2013. A review on the sealing structures of membrane electrode assembly of proton exchange membrane fuel cells. J. Power Sources 231, 285–292. https://doi.org/10.1016/j.jpowsour.2013.01.009.

Yeh, W.-C., 2011. Optimization of the disassembly sequencing problem on the basis of self-adaptive simplified swarm optimization. IEEE Trans. Syst. Man Cybern.-Part A Syst. Humans 42 (1), 250–261.

Yu-fei, X., Qiang, L., 2016. Partial disassembly sequence planning based on Pareto ant colony algorithm. 2016 Chinese Control and Decision Conference (CCDC). IEEE, pp. 4804–4809.

Yun, L., Linh, D., Shui, L., Peng, X., Garg, A., Le, M.L.P., Asghari, S., Sandoval, J., 2018. Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles. Resour. Conserv. Recycling 136, 198–208.

Zhou, Z., Liu, J., Pham, D.T., Xu, W., Ramirez, F.J., Ji, C., Liu, Q., 2019. Disassembly sequence planning: recent developments and future trends. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 233 (5), 1450–1471.

Zorn, M., Ionescu, C., Klohs, D., Zähl, K., Kisseler, N., Daldrup, A., Hams, S., Zheng, Y., Offermanns, C., Flamme, S., et al., 2022. An approach for automated disassembly of lithium-ion battery packs and high-quality recycling using computer vision, labeling, and material characterization. Recycling 7 (4), 48.

Züttel, A., Remhof, A., Borgschulte, A., Friedrichs, O., 2010. Hydrogen: the future energy carrier. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 368 (1923), 3329–3342.