FIT-4-AMANDA

Future European Fuel Cell Technology: Fit for Automatic Manufacturing and Assembly

EUROPEAN COMMISSION
Horizon 2020 | FCH-01-1-2016 | Manufacturing technologies for PEMFC stack components and stacks
GA # 735606

Deliverable No.	Fit-4-AMandA D1.2	
Deliverable Title	Analysis on the supportive technology for optimized manufacturability vs stack performance	
Deliverable Date	2018-02-25	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
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Status	Final	2018-02-26

Contents

Abbreviations

AFC	Alkaline fuel cells
AM	Anode module
BoP	balance of plant
BPP	Bipolar plate
CCM	Catalyst coated membrane → ionomer membrane with deposited catalyst layers
DMFC	Direct methanol fuel cell
EP	End plate
FC	Fuel cell
FCEV	Fuel cell electric vehicle
GDL	Gas diffusion layer
ICE	Internal combustion engine
LCV	Light-duty commercial vehicle
LT-PEMFC	Low temperature PEM fuel cell
MEA	Membrane electrode assembly
MMM	Mass manufacturing machine
NDT or NDI	Non-destructive testing / Non-destructive inspection
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cells
SOFC	Solid oxide fuel cell
SoA	State of the Art

1 Publishable Executive Summary

Fit-4-AMandA focuses on the industrialisation of stack components and stack assembly and delivering affordable fuel cell systems in larger quantities to saturate the emerging market demand.

The first step in the project, realised in task T1.1, is the formulation of the requirements specifications for the automatic machine that will be producing stacks, the centrepiece of the fuel cell systems. Such requirements include the demands on the technology for product manufacturing and also the product-oriented requirements for the processes of storage, supplying, assembly and handling. The requirements for the planned production system have to be defined in the same step, such as output cycle time and the kind of manufacturing and automation level, the general machine design, quality assurance system and special infrastructure requirements.

The content of this document is a technology and business study in the field of fuel cell technologies in the transport sector (parcel delivery), depending on government requirements (latest pollution laws, etc.) and focusing on the production aspects of fuel cells.

The updated version of the technical research on FC types shows that the PEM type remains the most promising version currently available. It exhibits advantages in terms of a rapid and easy start-up and the high power density. For this purpose, an overview is given of currently available FC cars, including applied FC types and stack condition and data.
Regarding the right balance between manufacturability and stack performance of a LT-PEMFC, the BPP and MEA are identified or confirmed as the key components. Furthermore, the gasket or seal fabrication is taken into account as the key fabrication process.
In addition, the components are described and their execution options are presented and evaluated with regard to the requirements arising from automated manufacturing.
The component design, joining and handling of the individual components result in the challenges to be solved in the automated assembly of stacks. For this reason research and analysis was carried out concerning the state of the art of present FC stack assembly systems with the scope of high automation levels.

Bottleneck of this process will be the availability of the core components in a way that the machine is able to handle it appropriately and ensure reliable feed into the process. This includes the transportation boxes, separation layers etc. Supply of these components should be realized in uniform cases / boxes for each component to have an optimal interface to the individual component manufacturer / supplier.

These components are mainly:

- MEA variants 7-L or FAST[1]-GDL including:
    - CCM with
        - Membrane
        - Catalyst
    - GDL
- Bipolar plate (in one piece that means not as single half plates)

[1] Since there is no “flip”-feature anymore as an essential part of FAST GDL this denomination is not correct but will be kept for the sake of simplicity.

2 Introduction

The content of this document is a technology and business study in the field of fuel cell technologies in the transport sector (parcel delivery), depending on government requirements (latest pollution laws, etc.) and focusing on the technical aspects.

It will give an overall outlook regarding future fuel cell EU targets, resulting in a pre-selection of relevant (present) stacks. The critical technical aspects related to the targeted production ratio will be given and illuminated.
In cooperation with WP 2, a review will be performed regarding advantageous manufacturing technologies and strategies: *WP2 Redesign current stack and stack design components for mass production and design to-cost.* For this purpose, an overview of state of the art manufacturing systems will be provided.

- *In close collaboration with the consortium partners the correct balance has been determined between manufacturability and stack performance. PM has predefined their current and their target automation, production rate and test cycle time for fuel cell stacks.*
- *EWii has calculated their current and their target automation and production rate of fuel cell stack components and important requirements regarding quality control and testing, supported by TUC.*
- *Based on this PM has also defined a plan for upscaling its balance of plant (BoP) component assembling capabilities to complement the implementation of the automated stack manufacturing. Critical technical aspects are pointed out regarding the targeted production ratio.*

In order to improve the understanding of the recommendations and related guidance developed in this report, reference to the main objective or product requirements of UPS (delivery service) shall be given.

For the delivery sector, it is important to have a range extender for the delivery cars. The demands placed on such range extenders by the parcel service are short charging or refuelling times, and much longer service life compared to privately used cars. However, features of the FC stack for LCV application especially as a range extender such as dimension, weight and power range tend to be subordinate to those prioritized in the private automotive sector. Other specifications may be more critical such as lifetime requirements of up to 20,000 operating hours or even more.

3 State of the art

3.1 Fuel cell EU targets

Currently the **Multi-Annual Work Plan 2014 to 2020** – Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) under the EU's new funding programme for research and innovation, Horizon 2020 – still shows the state of the art and future targets for transportation[2], which has already been referenced in Report T1.1[3].

3.2 Preselection of relevant present FC types and stacks

The currently most-promising FC technology for vehicles is the PEMFC (proton exchange membrane fuel cells). Other FC variants, already listed in Report 1.1, are direct methanol fuel cells (DMFCs), alkaline fuel cells (AFC), alkaline membrane fuel cell (AMFC), phosphoric acid (PAFC) and polymer phosphoric acid, molten carbonate (MCFC), solid oxide (SOFC). The reason why PEMFCs are the best FC-type for vehicle applications lies in their advantages in comparison to other currently available or developed / known FC options:

- Rapid and easy start-up,
- High power density,
- Solid state construction or design,
- High chemical-to-electrical energy conversion efficiency,
- Almost zero environmental emissions and
- Low-temperature operations (60 – 120 °C)[4;5].

Table 3-1 gives a short overview of FC powered vehicles presently available on the market. Furthermore, this table shows which FC and stack types are used in these vehicles. It is clear that the parcel-delivery sector, the business sector of UPS, has a particularly different demand compared to the commercial private vehicle sector – so the overview is seen as a basis for the following conclusions and decisions. However, similar to the future FC car market, the PEMFC technologies are also a strong candidate for future energy converters for the sector of transport vehicles[6].

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[2] Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) under the EU's new funding programme for research and innovation, Horizon 2020. Multi - Annual Work Plan 2014 – 2020, Adopted by the FCH2 JU Governing Board on 2014-06-30

[3] Scheffler, S.; Barthel, T.; Heidrich, J. (IWU): Manufacturing technologies for PEMFC stack components and stacks, REPORT - Business studies - Fit-4-AMandA D1.1 (GA # 735606). 2017-08-25

[4] Evangelisti, S. et al.: Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. Journal of Cleaner Production 142 (2017), pp. 4339 – 4355, Info from pp. 4342 point 2.3.1.1. Systems characteristic

[5] Yeetsorn, R.[1]; Fowler, M. W.[2] and Tzoganakis, C.[2]: A Review of Thermoplastic Composites for Bipolar Plate Materials in PEM Fuel Cells. Materials Science » Composite Materials » "Nanocomposites with Unique Properties and Applications in Medicine and Industry", book edited by John Cuppoletti,; King Mongkut's University of Technology North Bangkok[1] and University of Waterloo[2], [1]Thailand and [2]Canada; www.intechopen.com pp. 317 – 344; Published: August 23, 2011 under CC BY-NC-SA 3.0 license; p. 317

[6] A. Alaswad, A. Baroutaji, H. Achour, J. Carton, Ahmed Al Makky, A.G. Olabi, Developments in fuel cell technologies in the transport sector, International Journal of Hydrogen Energy, Volume 41, Issue 37, 2016, Pages 16499-16508, ISSN 0360-3199, [last access date: 2018-01-31; published on 2016] https://www.researchgate.net/publication/301729893_Developments_in_fuel_cell_technologies_in_the_transport_sector ; https://research-portal.uws.ac.uk/en/publications/developments-in-fuel-cell-technologies-in-the-transport-sector

Table 3-1 FCEV presently available on the market

No	Manufacturer and Model(s)	Production – Available on the Market since	Data Powertrain: FC Type and Stack type	Model Figures
1	Mercedes-Benz • GLC [7] FC initiative of Mercedes-Benz[8]: F-Cell (2010 – present)	**Sales launch: 2018** (GLC)	**FC type = PEM** P = 147 kW / 200 hp **Capacity** m_{H2} = 4.4 kg; Range = 437 km (NEFZ) η = 60 %	
2	Hyundai • Nexo [9] Predecessor models: • SUV iX35; Tucson FCEV	**Sales launch: 2018–present** (Nexo) **(model only for FC)**	**FC type = PEM** P = 120 kW / 163 hp Capacity m_{H2} = - (3 tanks, 52.2l of H_2/tank) Range = 800 km (NEFZ) η = 60 %	
3	Honda • Clarity Fuel Cell [10] Predecessor models: Honda FCX Clarity (2008–2014)	**Sales launch: 2016–present** (Honda Clarity Fuel Cell)	**FC type = PEM** P = 130 kW / 174 hp Capacity m_{H2} = 5 kg Range = 589 km (EPA) η = n.a.	
4	Toyota • Mirai [11; 12]	**Sales launch: 2015–present**	**FC type = PEM** P = 113 kW / 154 hp Capacity m_{H2} = 5 kg (2 tanks) Range = 500 km (EPA) η = n.a. *Each stack comprises 370 cells, with a cell thickness of 1.34 mm and weight of 102 g.*	

[7] Mercedes-Benz: GLC F-CELL startet in die Vorserie, [last access date: 2018-01-31; published on ---]. Available under: https://www.mercedes-benz.com/de/mercedes-benz/fahrzeuge/personenwagen/glc/der-neue-glc-f-cell/); http://www.sueddeutsche.de/auto/mercedes-glc-f-cell-die-brennstoffzelle-lebt-wieder-1.3652410

[8] Mercedes-Benz: Daimler Corporate Brochure 2017 PDF, [last access date: 2018-01-31; published on ---] https://www.daimler.com/documents/company/other/daimler-corporateprofile-en-2017.pdf

[9] Skarics, R.: Hyundai Nexo: Brennstoffzelle und Wasserstoff marsch!, [last access date: 2018-01-31; published on 2018-01-29]. Available under: https://derstandard.at/2000072752878/Hyundai-NexoBrennstoffzelle-und-Wasserstoff-marsch; https://www.hyundai.news/de/pressemappen-modelle/nexo-pressetext/, (20180109_PM_Hyundai_Nexo Präsentation_Jan_2018.pdf)

[10] Honda: Clarity Fuel Cell – A Clear Path to the Future, [last access date: 2018-01-31; published on ---]. Available under: https://automobiles.honda.com/clarity-fuel-cell; https://www.golem.de/news/elektroauto-die-brennstoffzelle-ist-nur-theoretisch-effizient-1512-117792.html

[11] Toyota: Der Toyota Mirai – Die erste Wasserstoff-Limousine in Großserie, [last access date: 2018-01-31; published on ---]. Available under: https://www.toyota.de/automobile/der-toyota-mirai.json;

[12] Green Car Congress: Toyota FCV Mirai launches in LA; initial TFCS specs, [last access date: 2018-01-31; published on ---]. Available under: http://www.greencarcongress.com/2014/11/20141118-mirai.html

The comparison of the currently available Fuel Cell Electric Vehicles (FCEV) in Table 3 1 shows that the car manufacturers active in this field all rely on the PEMFC technology. The performance range of the electric engines supplied by this energy converter technology spans from 113 kW to 147 kW. The typical requirements for cars regarding the energy converter comprise high efficiency, availability and range (tank size). The overall efficiency of the PEMFC stacks of Hyundai Nexo and Mercedes-Benz GLC is 60 % according to the manufacturers. Another common aspect of the four models is the application of metallic BPPs since they offer advantages regarding cost and installation space (plate thickness and also stack height) compared to composite graphitic BPPs.
The automotive fuel cells usually target 5000 h of operation, a figure appearing in the H2020 targets. This estimation is based on the assumption that passenger cars achieve on average 250,000 km of total mileage during their lifetime, with an average cruising speed of 50 km / h. This lifetime can be achieved by using metallic BBPs provided with anticorrosion coatings. For higher lifetime requirements e. g. in the field of the delivery sector graphite composite bipolar plates enable lifetimes of up to 20,000 or more operation hours, because of their excellent corrosion resistance.
Table 3-2 is an addition to Table 3-1 and serves as an overview for funded or published projects that address FC concepts or themes of the delivery vehicle sector.

Table 3-2 FCEV projects for parcel or delivery service

No	Manufacturer and Model(s)	Project	Content	Data Powertrain: FC Type and Stack type
1	UPS [13; 14] Project Sponsor U.S. DOE	Project ID: TV034 Center for Transportation and the Environment (CTE) 2016 DOE Annual Merit Review June 7, 2016	UPS Launching World's First Fuel Cell Electric Class 6 Delivery Truck	HyPMHD 16 kW and HyPM HD 30 kW
2	DHL [15] Project Sponsor NOW	H2 MOBILITY and StreetScooter have agreed upon an understanding for joint cooperation concerning the deployment of hydrogen mobility in the commercial vehicle sector.	"Deutsche Post DHL Group is now testing several hundred StreetScooter WORK L's equipped with fuel cell drives for the first time. These vehicles will be able to travel over 500 kilometres and Deutsche Post DHL Group is planning test runs for the next two years.	

[13] O'Dell, J. (UPS): UPS Launching World's First Fuel Cell Electric Class 6 Delivery Truck, [last access date: 2018-02-01; published on 2017-05-02]. Available under: https://www.trucks.com/2017/05/02/ups-fuel-cell-electric-delivery-truck/

[14] Hanlin, J.: 2016 DOE Annual Merit Review – Center for Transportation and the Environment (CTE), [last access date: 2018-02-01; published on 2016-06-07]. Available under: https://www.hydrogen.energy.gov/pdfs/review16/tv034_hanlin_2016_o.pdf

[15] DHL, [last access date: 2018-01-14; published on 2017-10-02; 2017-10-03; 2017-12-04]. Available under: http://www.dhl.com/en/press/releases/releases_2017/all/streetscooter_shifts_into_high_gear.html; https://cleantechnica.com/2017/10/03/deutsche-post-dhl-building-2nd-streetscooter-electric-van-factory-doubling-production-volume/; https://www.now-gmbh.de/en/news/press/h2m-and-streetscooter-cooperate-on-hydrogen-mobility

The powertrain data, FC types and stack types of Table 3-1 differ from the project goals listed in Table 3-2 regarding the targeted range, the required stack lifetime indicated in operating hours and the slightly less important stack height.

For example, the US-project by UPS (Project ID: TV034) investigated whether the FC energy converters HyPMHD with 16 kW and HyPM HD with a performance of 30 kW, serving as range extenders, are enough to realise various delivery routes without refuelling. The goal was, to meet the vehicle performance specifications of contractual and fleet operators in comparison to existing delivery vans (diesel, CNG, electric). Approximately 97 % of class 3-6 Delivery Van deployments require < 125 mile range. In order to fulfil this requirement existing route length capability of zero-emission delivery vans is to be increased from 70 miles to 125 miles. The approach was to model the project vehicle to ensure components are sized appropriately for 125 mile range[16].

Further examples of FC projects considering and developing the FC technology for trucks include:

- COOP truck in Switzerland (PEM-Stack, P = 100 kW)[17]
- VDL Konzept[18]
- Toyota FC-Truck (Class-8-Truck) with 670 hp, powered by two fuel cell stacks of the Toyota Mirai[19]

[16] Hanlin, J.: 2016 DOE Annual Merit Review – Center for Transportation and the Environment (CTE). [last access date: 2018-02-01; published on 2016-06-07]. Available under: https://www.hydrogen.energy.gov/pdfs/review16/tv034_hanlin_2016_o.pdf

[17] HZwei-Blog: Erster Wasserstoff-Truck auf der Straße. [last access date: 2018-02-01; published on 2017-09-07]. Available under: https://www.hzwei.info/blog/2017/09/07/erster-wasserstoff-truck-auf-der-strasse/

[18] SMMT: Long haul fuel cell project gets green light. [last access date: 2018-02-01; published on 2017-06-14]. Available under: https://www.smmt.co.uk/2017/06/long-haul-fuel-cell-project-gets-green-light/

[19] Prawitz, S.: Toyota testet Brennstoffzellen-Lkw. [last access date: 2018-02-01; published on 2017-04-17]. Available under: https://www.automobil-industrie.vogel.de/toyota-testet-brennstoffzellen-lkw-a-602467/

4 PEMFC technology

4.1 Configuration or assembly variants of present FC stacks

Figure 4-1 shows different components of PEMFC system, taking into account the sub-assemblies hierarchy to be considered[20]. The MMM will produce the PEMFC stack (marked green). All additional components will be also realised in the scope of the project (by PM and UPS respectively sub-contractors).

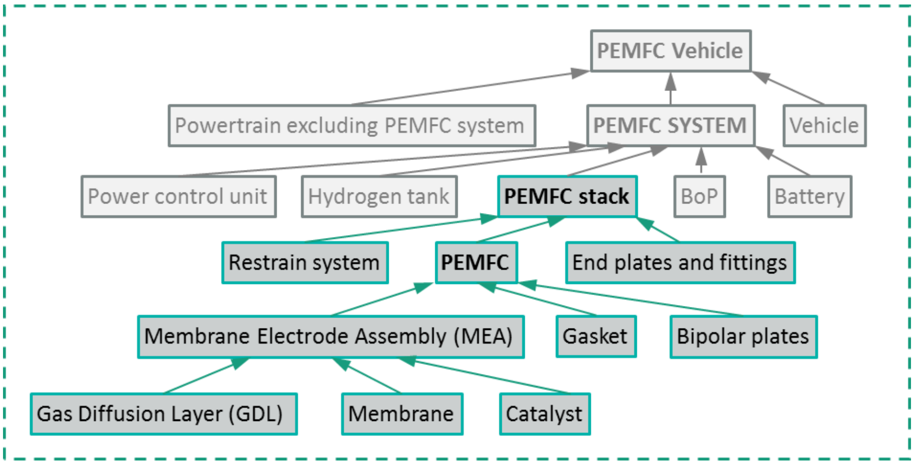


Figure 4-1 PEMFC vehicle components, hierarchy and areas relevant for the report

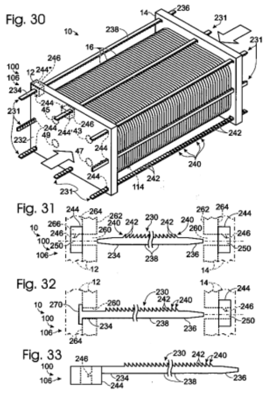
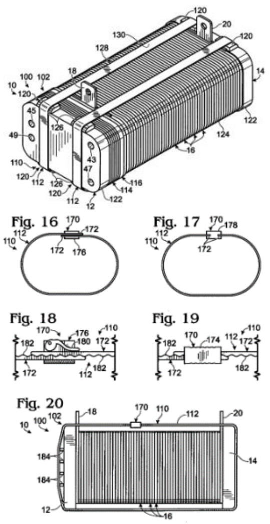
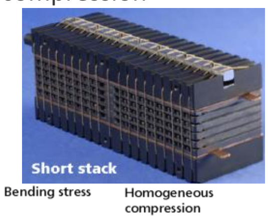
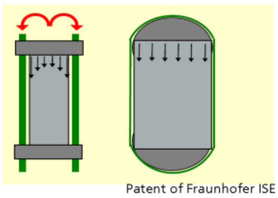
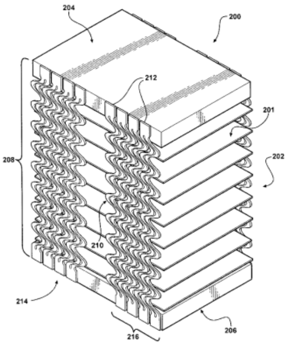
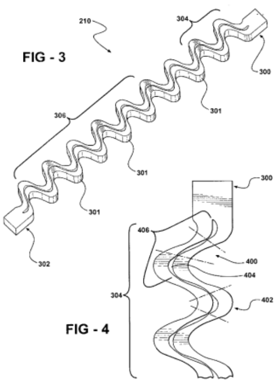
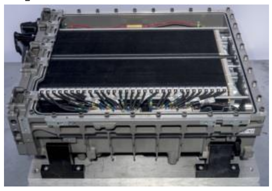
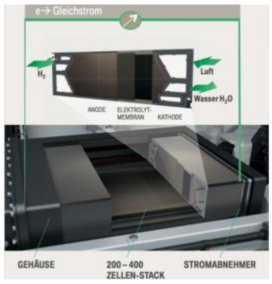
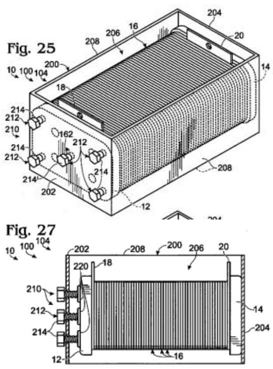
PEMFC consists of different components which are manufactured using different processes and until now have been finish-assembled manually[21]. As the demand for PEMFC is expected to increase rapidly, with many new applications awaiting realization, it is essential to use automated manufacturing and assembly line for FC production.

A restrain system is required to compress the stack after stacking and during its “life time or cycle”. There are several solutions whose principal design variants are shown in Table 4-1.

[20] Evangelisti, S. et al.: Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. Journal of Cleaner Production 142, 2017, pp. 4339 – 4355, Info from pp. 4341 - 4342

[21] Lehner, F. et al.: Massenfertigung für PEM-Brennstoffzellen – Entwicklung eines Massenfertigungsverfahren für Komponenten einer PEM-Brennstoffzelle; Berichte aus Energie- und Umweltforschung, 2006
Available under: https://nachhaltigwirtschaften.at/resources/fdz_pdf/endbericht_0625_pem-brennstoffzelle.pdf; www.FABRIKderZukunft.at

Table 4-1 List of present stack compression or restrain systems and concepts

Restrain system concept with tie rods E. g. PM	**Restrain system concept with bands** E. g. US20060093890 A1 and ISE	**Restrain system concept using planar strips** E. g. US20080145713 A1	**Restrain system concept with a frame adjusting screws** E. g. BMW and US20080145713 A1
Tie rod positioned outside the plates e. g. PM[22]:  Pictures approached form **US 20060093890 A1:**  Tie rod positioned within the plates[23]:	Pictures approached form **US20060093890 A1:**  **ISE** - Homogeneous compression[24]  	Pictures approached form **US20060093890 A1:**  	"BMW-Brennstoffzelle-Wasserstoff-Technik-07" [25] [**BMW fuel cell**-hydrogen technology 07]:   Pictures approached form US **20060093890 A1:** 

[22] Proton Motor: PM 200 und PM 400 Stack, [last access date: 2018-02-01; published on 2016-06-07]. Available under: http://www.proton-motor.com/pm-400-stack-2/?lang=de; http://www.proton-motor.com/wp-content/uploads/2013/11/PM_200_GenA_V4_Datenblatt_deutsch.pdf, http://www.proton-motor.com/wp-content/uploads/2013/11/Datenblatt_PM-400_GenA_96Zeller_1_400_004_Rev.01.pdf

[23] Dana Power Technologies (NYSE: DAN), REINZ-Dichtungs-GmbH: Dana presents fuel cell technology at the Hannover Trade Fair, MAUMEE, Ohio, [last access date: 2018-01-31; published on 2013-04-08]. Available under: http://www.reinz-industrial.com/DE/NEWS/Presse.aspx?sstr=1

[24] Fraunhofer ISE: HT- and LT-PEMFC Stacks for Portable Applications, Stack design with simple assembling technology, [last access date: 2018-02-01; published 2010-04-23]. Available under: http://www.h2fc-fair.com/hm10/images/pdf/fraunhofer04.pdf

[25] BMW: BIMMERTODAY, [last access date: 2018-02-01; published on 2016-06-07]. Available under: http://www.bimmertoday.de/2015/07/03/bmw-brennstoffzelle-interview-mit-antriebsforscher-klietz/

4.2 Key components of the pre-selected relevant (present) stacks

Table 4-2 gives an overview regarding the state of the art of materials and manufacturing processes of the most important PEMFC components. The components, used materials and manufacturing processes or technologies are summarised and presented in the following table:

Table 4-2 Materials and manufacturing processes of the most important PEMFC components

Component	Material and variants	Manufacturing / fabrication	Names of important manufactures
Bipolar plate	Traditional non-porous graphite, composite graphite (thermoset bulk moulding compounds), stainless steel, aluminium-, titanium- and nickel alloys	Sheet metal forming, coating, milling, die casting, injection moulding (afterwards extrusion, hotpressing or calendering), compression moulding	**For metallic:** • Borit Leichtbau-Technik GmbH • ElringKlinger AG • Gräbener Maschinentechnik GmbH & Co. KG (Wall thickness from 50 µm) • Nuvera Fuel Cells, Inc. • Sumitomo Metal Mining Co., Ltd. (& NIPPON STEEL) • DANA Holding Corp. **For composite:** ***Injection mould*** • Eisenhuth GmbH&Co. KG ***Compression mould*** • EWII Fuel Cells A/S • Entegris Inc. • Dana • Metro Mold & Design, Inc. • Nisshinbo chemicals Inc.
Catalyst	**Catalysts cathode:** Pt Pt-Co-Cr Pt-Ru-Sn **Catalysts anode:** Pt Pt-Ru Pt-Rhodium Pt-Sn **Substrate:** graphitised carbon black Colloids Titan suboxide	Screen printing, spraying, pressing Nowadays, PTFE, FEP, PFA, PVDF and PVA bound, platinum-containing carbon particles in macro porous carbon fibre, fiberglass or plastic mats hot pressed and then coated with precious metals and pressed with the PEM.	• Johnson Matthey plc. • Degussa Metals Catalysts Cerdec AG, (Dmc) • Umicore AG & Co. KG • Heraeus Holding GmbH

	[26]	For better CO compatibility towards the gas side increasingly ruthenium-containing catalyst layers are applied (US 5795669). [27]	
Commercial PEM / CCM[28]	Nafion™ perfluorosulfonic acid (PFSA) = Ion Exchange Materials- N115, N117, N1110 (producer and distributor is DuPont – data sheet) [29] • [GORE Select® • HOECHST CELANESE • BAM3G® (BALLARD) • Flemion® (ASAHI GLASS) • Aciplex® (ASAHI CHEMICAL) • Neosepta® (TOKUYAMA) • Raipore® (PALL RAI) • Ionac® (SYBRON CHEMICALS) • Hyflon® (SOLVAY S.A.) • Fumion® FUMATECH][30]	Spraying, drawing, casting, pressing; extrusion cast membranes	• EWII Fuel Cells A / S • DuPont, Corp. • Gore & Associates, Inc. • Hoechst AG • Celanese Corp. • Ballard Power Systems Inc. • Asahi Kasei Corp. • Tokuyama America, Inc. • Pall RAI Inc. • Sybron Chemicals Inc. • Solvay SA • fumatech GmbH
Anode and cathode GDL	Carbon cloth - nonwoven[31], carbon papers	Carbonised fibres (paper or textile)	• Freudenberg FCCT SE Co. KG • SGL Carbon SE • Toray Industries, Inc. • Ballard Power Systems Inc. • CE-Tech • Hollingsworth & Vose GmbH • JNTG • AvCarb Material Solutions • Nuvant Systems Inc.

[26] Kurzweil, P.: Grundlagen, Komponenten, Systeme, Anwendungen, Brennstoffzellentechnik. Springer Vieweg, Wiesbaden, 2013, p. 86
[27] Kurzweil, P.: Grundlagen, Komponenten, Systeme, Anwendungen, Brennstoffzellentechnik. Springer Vieweg, Wiesbaden, 2013, p. 86

[28] Both, manufacturers of naked perfluorinated membranes and suppliers of catalyst coated membranes are listed here for the sake of simplicity

[29] Chemours™ Product Bulletin P-12, [last access date: 2018-01-31; published on x]. Available under: https://www.chemours.com/Nafion/en_US/assets/downloads/nafion-extrusion-cast-membranes-product-information.pdf
[30] Kurzweil, P.: Grundlagen, Komponenten, Systeme, Anwendungen, Brennstoffzellentechnik. Springer Vieweg, Wiesbaden, 2013, p. 79

[31] FREUDENBERG FCCT SE CO. KG, [last access date: 2018-01-31; published on x]. Available under: https://fuelcellcomponents.freudenberg-pm.com/Products/gas-diffusion-layers

Gasket, sealing → Principle variants[32]: • Loose gaskets (supported or unsupported) • Integrated designs onto metal or graphite bipolar plates • Softgoods such as GDL, MEA and MEA frame material	LT-PEM applications[32]: • Silicone material, 40 FC-LSR100 • Superior polyolefin elastomer, 35 FC-PO100 Examples of sealing solutions[33]: • Fast GDL • Seal integration on metal BPP module and also graphite BPP • Ice Cube Sealing	Injection moulding of special TPE polymer suitable for fuel cells	FREUDENBERG SE CO. KG
(End plates / caps)	Aluminium alloys Fibre reinforced Epoxy SS	Milling, casting	-

[32] FREUDENBERG FCCT SE CO. KG, [last access date: 2018-01-31; published on x]. Available under: https://fuelcellcomponents.freudenberg-pm.com/

[33] FREUDENBERG FCCT SE CO. KG, [last access date: 2018-01-31; published on x]. Available under: https://fuelcellcomponents.freudenberg-pm.com/Products/fuel-cell-stack-seals

4.3 Review of manufacturing technologies and strategies

FC stack assembly with scope to high degree of automation

First, it should be noted that during the processing period no text sources could be researched, which contained useful information regarding automated stack manufacturing. For this reason, publicly available video sources were also included in the research and are described in the following.

Stack Concepts

Reference[34] shows the manual assembly of a FC stack. A worker manipulates the BPP with a seal applied to the endplate. The vertical positioning is ensured by a 3-sided system. The stack comprises a "chemically treated paper" (which conducts both gas and electricity), a catalyst coated membrane (splitting protons and electrons and running the electrochemical reaction) and at least a BPP for a FC. These steps are repeated in relation to the number of FCs. This sequence is repeated until the stack reaches its final height or fuel cell count. After assembling the stack, Technicon compresses the FC stack in a hydraulic press for obtaining a quality control test and aggregation. Before the stack is released from the press, high-strength steel rods are installed for compressing the cells– in this case with a load of 3 tons.

Reference[35] shows a robotic stack assembly of ceramic FCs, with 2 Kawasaki robots. Robot 1 sets the components (also the quadruple frame) to the camera position. Afterwards Robot 2 takes them and stacks them. The supply apparently takes place using metal "shaft magazines".

The following described video with the reference[36], is a project product of the company "JEFFREY GUEBLE – Director of Engineering at Zetec Inc", where a plant for stacking was built for the company Ballard. The stacking is realised using a "Fanuc LR Mate 200" robot in a simple sloping tower – the lower end plate is underneath. The supply takes place via shaft magazines (possibly adjustable), in which the robot travels exclusively.
The system has a turntable for swivelling the inclined or slightly tilted press unit. The upper media module is guided during pressing in order to compress or tension the stack. The stack is secured in position during pivoting.

References [34, 35] and [36] show laboratory facilities which provide approaches for automated production of FCs or FC stacks.
Due to the demand of developing and providing an automated plant ready for mass production, numerous requirements have to be fulfilled, for example

- Ensuring of highest precision,
- Highest repeating accuracy,
- Automation-oriented provision of the individual components,
- Automated handling of sensitive components (sensitive regarding their robustness),
- Enabling a high level of technological flexibility (e. g. scalability, handling of different materials and component designs etc.)
- Tracking of products and batches.

This is associated with certain risks and requires a maximum of development achievement.

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[34] How It's Made - Elcore GmbH: How It's Made Hydrogen Fuel Cells, video, [last access date: 2018-01-31; published on 2015-05-05]. Available under: https://www.youtube.com/watch?v=LDwS31OE7ak

[35] TF Automation: Robotic Stack Assembly, video, [last access date: 2018-01-31; published on 2015-07-10]. Available under: https://www.youtube.com/watch?v=kIjsnGubDW8

[36] Jeff Gueble: Fuel Cell Assembly, video, [last access date: 2018-01-31; published on 2016-12-25]. Available under: https://www.youtube.com/watch?v=lLQAQEF36-U; https://www.jgueble.com/; https://www.jgueble.com/fuel-cell-assembly; © 2016 by JEFFREY GUEBLE

5 Discussion and Conclusions

Approaches for Improvement: Supportive technology for optimized manufacturability vs. stack performance in respect of the desired application – Investigation of advantageous manufacturing technologies and strategies, considering the stack performance and lifetime have been carried out.

General approach:

- reduction of process time
- enhancement of flexibility
- high process reliability
- high performance of the component MEA in combination with the BPPs and sealing / gasket

Conclusion – the following suggestions are resulting from the described work package tasks:

a) All selected material have to be supplied in a way that the machine feed-in can be realised quickly and easily, that means in one piece and without complicated separation steps (e. g. interlayers etc.)
b) By using novel CCMs, the overall stack performance may be improved. Therefore PM should perform a benchmark test (remark: GDL may also be in this focus but appears to be not so crucial - the best CCM / MEA performance in combination with the best GDL should be selected).
c) Metallic bipolar plates (BPP) are not preferable due to higher lifetime demands of the desired application than actually realisable with SoA coating technology. Furthermore with graphitic BPP a higher degree of flexibility is given in terms of flow field design, which also implies operation parameters and periphery components.
d) Fall-back solutions for different stack technologies must be realisable with the MMM e. g. 7-L MEA vs. (FAST) GDL / CCM or restrain concepts.
e) Strategically it is mandatory to have more than one supplier of key components (second source). This also affects key components of the CCM / MEA (membrane, catalyst etc.) and BPP (mould raw material) production of EWII.
   Main reason is the currently still unstable market situation of suppliers and manufacturers. Besides that, further cost optimisation of the components should be targeted after finalising the project to assure market readiness and competitiveness.
f) Secure availability of materials and components has to be assured.
g) Freedom of scalability: to serve several markets and to use synergies, it would be highly recommended that the MMM is capable to produce a variety of stack formats and sizes e. g. several cell numbers or PM 200 as well as PM 400 (and possibly future stack formats and generations) without high additional efforts / reconstruction. This will enable PM to serve several markets / delivery vehicle and truck classes (class 3 to class 8).

During the close collaboration work in the project FIT-4-AMandA, it has become clear that the MEA and the BPP are the important key components – by focusing the optimisation of the manufacturability vs. stack performance.

The effects of the new approaches for the improved manufacturability with the MMM is shown in Table 5-1.

Table 5-1 Balance between manufacturability and stack performance

<table>
<tr><th>Components</th><th>State of the art manufacturing technique</th><th>Technique used in F4A project[37]</th><th>Advantages</th><th>Disadvantage</th></tr>
<tr><td rowspan="2">MEA+GDL</td><td rowspan="2">Die cut CCM + Freudenberg FAST GDL with hinge for a fast manual process</td><td>Die cut CCM + Freudenberg FAST GDL without hinge for a fast automated process</td><td>Both should be possible to be handled
CCM may come direct from roll but possibly expensive FAST GDL with injected seal</td><td>dependence on one supplier (Freudenberg) of the FAST GDL</td></tr>
<tr><td>7-Layer MEA with CCM, sub gasket and fixed GDL</td><td>independence of manufacturers, likely less expensive solution (overall)</td><td>sealing on BPP necessary</td></tr>
<tr><td rowspan="2">BPP</td><td>Graphitic composite plate in two separate half plates sealed with inlay gasket
Footprint with protruding voltage monitoring feature (“ears”)</td><td>Bonded graphitic composite plate with redesigned footprint shape (without ears – voltage monitoring is still possible with adapted monitoring unit</td><td>Better handling and automated processes
• Less time consuming
• Less error-prone
• More robust</td><td>Bonding technology has to be established by manufacturer (EWII)
• Cell voltage monitoring unit CVMU has to be adapted slightly</td></tr>
<tr><td>PM’s proprietary flow field design on cathode, cooling and anode</td><td>Optimised new flow field structures</td><td>Better performance
Use of more periphery components possible</td><td>New BPP tool necessary</td></tr>
<tr><td rowspan="2">Restrain concept</td><td rowspan="2">Tie rods and external plate strings</td><td>Tie rods and external plate strings</td><td>Approved technology, Thinner end plate system</td><td>Less easy to mount and handling of the stack (transportation)</td></tr>
<tr><td>Tie rods and internal plate strings</td><td>Easier stack mounting
• Easier stack handling
• More robust restrain system</td><td>Enhanced end plate thickness
Further interlayer plate required (little more expensive)</td></tr>
</table>

[37] When two possibilities are shown both should be manufacturable with the MMM

6 Risk Register

The identified risks are connected to the market entrance of this technology. Other risks, especially technical risks, will be found within the related WPs.

Table 2 Risk Register

Risk No.	What is the risk	Probability of risk occurrence[38]	Effect of risk[39]	Solutions to overcome the risk
1	Economical risks: The unit-targets connected to the fuel cell technology are too progressive. → Stacks will be more expensive because of oversized production lines	Medium	Medium	Market monitoring and modification of the production lines to reduce the production cost
2	Political risks: The periphery of fuel cell technology is not ready at point of point of entrance. → Fuel cell cars available but H_2-stations missing	Low	Medium	The building of H_2 stations has to be accelerated by government before market entrance
3	Technical risks: 1) No availability of (a) machine suitable component(s) 2) Development or availability of new coatings with high corrosion protection of metallic BPPs	Medium	Medium	1) More than one supplier of key components (second source) 2) The assembly plant should have a high level of technology flexibility

[38] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

[39] Effect when risk occurs: 1 = high, 2 = medium, 3 = Low

7 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

No.	Partner	Partner Full Name
1	UNR	Uniresearch BV
2	PM	Proton Motor Fuel Cell GmbH
3	EWII	EWII Fuel Cells A / S
4	USK	USK Karl Utz Sondermaschinen GmbH
5	Fhg	Fraunhofer IWU, Institute for Machine tools and Forming technology
6	TUC	Technische Universitaet Chemnitz, ALF, Department of Advanced Powertrains
7	UPS	UPS Europe SA

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 735606. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY.