FIT-4-AMANDA

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Contents

Publishable Executive Summary

Fuel cells are an excellent opportunity to meet the challenges of future energy supply. The core components and cost drivers of a polymer electrolyte membrane fuel cell stack (PEMFC stack) are the bipolar plate (BPP) and the membrane electrode assembly (MEA).

Report D2.5 deals mainly with BPPs; this is a public version of more detailed confidential report (which is submitted as D2.4).

BPPs have a significant impact on stack dimensions, performance and lifetime as well as on the cost of a PEMFC stack. The challenge is to design an optimal BPP for specific applications, taking into account the manufacturing effort and costs.

Basically, two material concepts are currently available: **Polymer composites** or **metals**. In comparison to metallic BPPs, graphite polymer composite BPPs have a longer lifetime and allow a high geometric flexibility. Metallic BPPs have a comparatively low overall thickness resulting in a lower cell pitch and thus higher volumetric power density of the PEMFC stacks, which makes them predestined for use in the commercial automotive sector. Not only that the base materials mentioned above have different application properties, but there are also differences regarding their processing, i.e., the different manufacturing methods, each of them having different opportunities and restrictions. Therefore, this report D2.5 presents a comparison and evaluation of BPPs with regard to possible manufacturing processes, properties and the resulting costs. The complete information is to be found in the confidential report D2.4. In this document, a summary of the public information is presented.

The decision to use graphite-polymer composite BPPs was made in the first period of the overall research project (decision of the project consortium, in particular the stack manufacturer and the intended end user, see report D1.2). For this reason, no functional BPP was designed and implemented to prove the manufacturability of the metallic BPPs. Instead, a flow field section was defined which contains significant geometric features of a BPP (basic geometry). A parameter study was carried out based on this basic geometry to prove the manufacturability by forming

Finite element simulation was used for a theoretical feasibility analysis of the forming process. To verify the obtained findings, a tooling system for hollow embossing of metallic BPPs was developed and manufactured. Thus, the theoretical findings could be successfully verified in real tests. Based on the knowledge gained, regarding the production of metallic BPPs, the manufacturability of functional BPPs can be predicted with a higher degree of certainty.

To analyse the MMM (Mass Manufacturing Machine) concept, it was not necessary to test the functionality of the assembly line developed in the project (in WP4) with a functional metallic BPP. The supply, feeding, picking up and manipulation of metallic BPPs can be guaranteed with the system developed for the graphite polymer composite BPPs in MMM. Fundamental changes to the MMM concept in WP4 are not necessary in order to handle and process both types of BPPs.

1 Introduction

In PEMFC stacks, BPPs are needed to supply the electrochemical active components of the fuel cell (i.e., anode and cathode catalytic layers) with hydrogen and oxygen/air as well as for removal of the reaction product (which is pure water), for providing a structural support to the MEA, conducting electrons, which participate in the electrochemical reactions, and for a dissipation of the reaction heat.

Because the BPP is a major structural element, the choice of BPP has a significant influence on stack dimensions, stack performance (different geometry of the channels due to different machining options) and stack life (different corrosion resistance), as well as stack costs. Continuous optimization is aimed at all of these areas. In general, the challenge is to develop an optimal BPP for the specific application, taking the manufacturing possibilities and the overall costs into account. Depending on the specific requirements and general conditions for performance and service life, but also for size, weight and heat dissipation, the optimal solution for the respective application may vary. For the manufacturing of BPPs, two materials are mainly used. Either the BPPs consist of polymer-based composite materials (polymer resin mixed with conductive fillings such as graphite) or metals. These are therefore mechanically processed with different processes or procedures to produce a channel structure of bipolar half plates (BP-HPs) and finally BPPs.

In the scope of the Fit-4-AMandA project [1], a comparison of possible process chains and production scenarios for the production of BPPs was carried out. The costs that are influenced by different scenarios were considered, too. These were used to benchmark the different material concepts and suitable processes for the production of BP-HPs and BPPs. In addition, a consideration of use cases, application areas and error sources as well as the representation of the production rates estimated as realizable was carried out.

General information about BPPs
As one of the core components of a PEMFC stack, the BPPs have three main tasks:

- Ensuring the supply of the reaction gasses hydrogen and air
- Removal of unreacted gases and product water (liquid and vapour)
- Conduction of thermal and electrical energy

For mobile applications of PEMFC stacks, relatively low service life requirements of approx. 5,000 to 8,000 operating hours are currently sufficient [2–5]. In comparison, stationary applications require service lives of approx. 20,000 to 40,000 operating hours and more [2].[1] The application cases for metallic and graphitic BPPs are derived mainly from the required service life and other properties of the relevant BPP materials. It is therefore imperative to further develop metallic BPPs in parallel with composite ones to be able to use and expand their potential for the different areas of application. The main application types are portable (transportable units), stationary and transport (vehicles for the transport of persons and goods). For example, PEMFC stacks used in vehicles are categorised as a transport application, because the unit for energy conversion is transportable but fixed in the vehicle. In the automotive sector, stainless steels and titanium are currently the favoured materials for BPPs. Titanium is chemically comparatively more robust and thus more resistant in the fuel cell environment.

However, it can be assumed, that as soon as the production volumes increase, the higher costs resulting from the use of titanium can no longer be subsidised by an automotive manufacturer. It is therefore a great motivation to qualify stainless steels, which are more cost-effective and easier to process, but much less resistant to the chemically aggressive environment in the PEMFC stack. Thus, corrosion-resistant but cost-effective coatings must be used. The use of noble metals as coating, e.g., gold, though demonstrated, is not commercially profitable. Therefore, from an economic point of view, metallic BPPs are currently not able to fully replace BPPs made of composites. However, the use of alternative metal alloys, e.g., stainless steels, in combination with innovative coating systems tailored for PEMFCs, allows metallic BPPs to be competitive.

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[1] Jennifer Kurtz, Sam Sprik, Genevieve Saur, and Shaun Onorato, *On-Road Fuel Cell Electric Vehicles Evaluation: Overview*. Technical Report: NREL/TP-5400-73009. Accessed on: Nov. 13 2019. Available under: https://doi.org/10.2172/1501673

2 Methods and results

In the following text passages, FC components for PEMFC stacks and processes for their manufacturing are presented.

2.1 Analysis for the production of fuel cell components

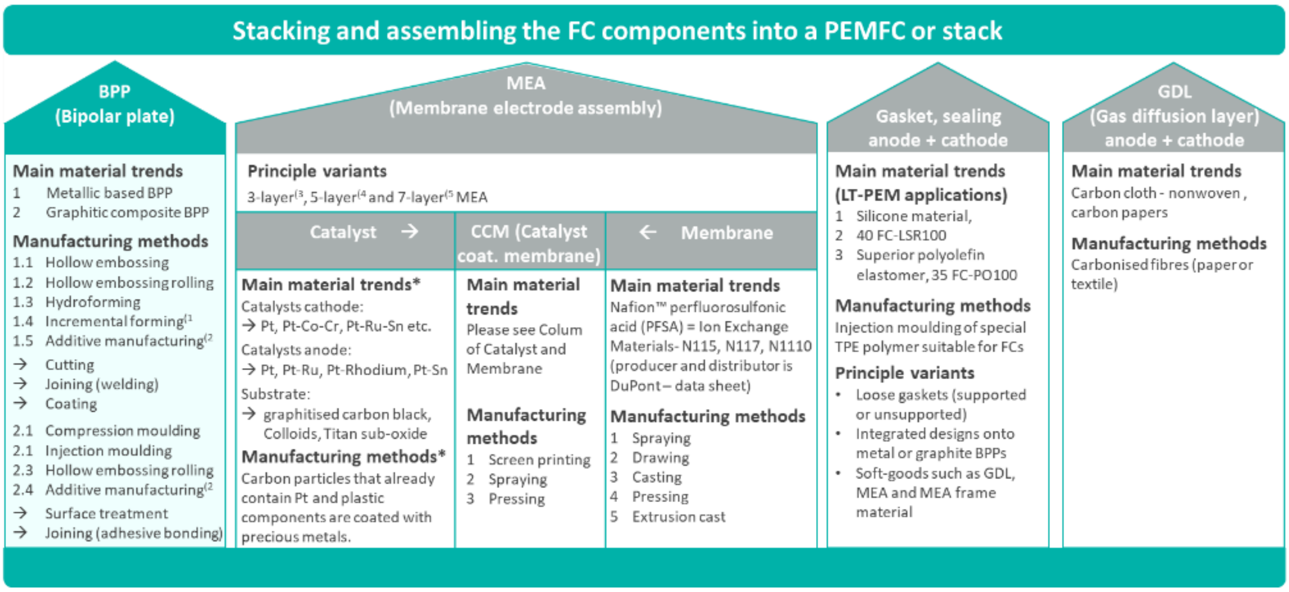

Figure 2-1 Overview on basic components of a PEMFC.

1. Bipolar plate

Materials and variants:

Traditional non-porous graphite, composite graphite (thermoset bulk moulding compounds), stainless steel, aluminium-, titanium- and nickel alloys.

This report focuses on the different manufacturing methods of bipolar plates. In principle, as already described, a distinction is made here between metal-based and graphite-based BPP. Accordingly, the production methods differ depending on the concept. Detailed explanations of these manufacturing processes and the possibilities associated with them are given in the overview publication [6] which was produced as part of the project. Excerpts from it are discussed in this report.

2. MEA - Membrane Electrode Assembly

A MEA or Membrane Electrode Assembly is the heart of a PEMFC. It contains the materials necessary to facilitate electrochemical conversion of a fuel to electrical energy. It consists usually of a polymer electrolyte membrane with catalyst loaded electrodes on each side. Remark: There are other concepts, but this one is prevalent by far.

2a) Catalyst

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.[2] For better CO compatibility towards the gas side increasingly ruthenium-containing catalyst layers are applied (US 5795669).

2b) Membrane

Usually the CCM consists of Nafion® i.e. (2-[1-[Difluor[(trifluorethenyl)oxy]methyl]-1,2,2,2-tetrafluorethoxy]-1,1,2,2-tetrafluorethansulfonic acid, or related ionomers in order to realise the transport of the protons from

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[2] There are however innovation projects (e.g., MAMA-MEA – Grant Agreement #779591) focused on additive manufacturing of MEAs, which would eliminate the bottleneck given by the hot pressing.

anode to cathode side. Additionally, this material has to be non-conductive for the electrons and has to show a high gas barrier functionality. Often it is reinforced with expanded PTFE.

Since this product is based on fluorine chemistry, the manufacturers of the CCMs are considered to be the specialists of this technology.[3]

Datasheet of producers and distributors of DuPont:[4]

- 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]

3. Gas diffusion layer (GDL)

The role of the GDL is also central: the GDL must distribute all gases optimally to the electrodes of the CCM and remove water, heat and electricity. The more homogeneously the gases are distributed and the more evenly the entire cross-section is flowed against, the more electricity is produced and the power density of the fuel cell increases.

The material of the GDL for PEMFC is usually based on carbonised fibres. There are different possibilities:

a) carbonised paper
b) carbonised cloth
c) carbonised non-woven / fleece

In order to fulfil all the above-mentioned transport tasks, a conductive carbon structure is impregnated and coated with specially developed substances. Binding fluoropolymers allow the liquid to bead up so that the material does not become soaked up with water. Thanks to its movable fibre structure, the carbon fibre structure of FPM can be easily pressed during the production process without being damaged.

Overall, GDL is therefore an essential component in simplifying production and increasing the performance and service life of the fuel cell. The tasks of the GDL in detail:

- Management of all transport functions from the CCM to the bipolar plate: hydrogen to the CCM anode side, atmospheric oxygen to the CCM cathode. Water transport from the anode to the bipolar channel structure.
- Heat dissipation: Dissipation of the reaction heat.
- Electrical transport: Discharge of the anode-side electrons. This is achieved by the appropriate use of highly conductive raw materials.
- Mechanical tolerance compensation: All components have component tolerances. Even the GDL, which can, however, deform locally, and thus absorb tolerances of adjacent components.
- Process reliability: The GDL is further processed in various processes. For this purpose it is robust and can be rolled without any problems due to its special carbon fibre base structure. (Remark: Carbon-paper based GDLs cannot be rolled easily on small radii without breakage.)
- Protection of the membrane: Membranes used in fuel cells are very thin and at the same time exposed to high loads. The special surface of the GDL protects the membrane from unacceptable loads during operation.

Usually, the GDL manufacturers come from one of the following technologies: carbonising, non-wovens, etc. Globally, there are many players on the market. Some of the important GDL manufacturers worldwide are:

- SGL
- Freudenberg
- AvCarb
- Toray
- Teijin
- Mitsubishi Chemical Corporation
- Cetech

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

[4] Chemours™ Product Bulletin P-12, [last access date: 2018-01-31]. Available under: https://www.chemours.com/Nafion/en_US/assets/downloads/nafion-extrusion-cast-membranes-product-information.pdf

4. Gasket, sealing

Main task of this sub-gasket is to separate the gas areas of anode from cathode side. In commercial products several concepts have been implemented for this task:

Sealing on BPP or CCM:

Examples of sealing solutions for LT-PEM applications[5]:

- FAST GDL
- Seal integration on metal BPP module and also graphite BPP
- Ice Cube Sealing

Sub-gasket (Guardket)

Often and also within the Fit-4-AMAndA project, CCMs are equipped with a so-called sub-gasket. Therefore, it is fixed directly to the CCM. Usually it consists of polyethylene naphthalate (PEN) films due to its well-suited properties.

Detailed description, tests and analysis of the different solutions are explained in detailed in the confidential report D2.4.

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[5] 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

3 Elaboration of principle differences

3.1 Differences resulting in used materials

The knowledge used in the project regarding typical materials used for BPPs is presented in the publications [7,8]. These deal in part with material production, material properties and, in particular, the processes for producing BPPs.

Within the framework of the Fit-4-AMandA project, in particular the stainless steel 316L (ASTM) was used for investigations into the production of metallic BPPs. It was possible to prove that this material is suitable for the production of metallic BPPs, among other things due to its ability to change shape. In particular, it was confirmed that material thicknesses of 0.100 mm, 0.075 mm and 0.050 mm are suitable in principle for the forming of functional flow field structures.

Special attention must be paid to the initial condition of the coil material before forming. The rolled and thus solidified coil material is to be treated by an idealised recrystallisation or bright annealing. This eliminates the consequences of cold forming, but without causing an α-γ transformation (α-ferrite-austenite transformation) of the crystal lattice. It is important that after bright annealing at least 5 or more grains predominate over the material thickness (microstructure). Otherwise, plastic deformation according to Mises (von Mises criterion) is not possible or can only be realised below the theoretically possible deformation capacity of the metallic material.

3.2 Differences resulting in used technologies

As stated in 3.1, the differences in possible manufacturing processes for BPPs are discussed in detail in the publications generated in the Fit-4-AMandA project [7,8].

Due to the decision of the Fit-4-AMandA project consortium to produce graphite composite BPPs and use them for the PEMFC stack, no metallic BPP was developed in the project. For the production of the graphite composite BPPs, the project partner IRD used the compression moulding process. The necessary tooling and equipment technology were developed for this within the scope of the project. A detailed description of this work can be found in the reports for WP3.

In parallel, the potential manufacturing processes of hydroforming, hollow embossing and hollow embossing rolling were considered theoretically for metallic BPPs. The results are published in [7,8]. Among other things, a basic estimation of production rates: This parameter is highly dependent on the technology chosen and varies **approximately** between 5 and 120 BPPs/min.[6] (These values are estimated and, as far as it is known, have not yet been extensively verified. This applies in particular to the hollow embossing process) [7,8].

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[6] Porstmann, S.; Wannemacher, T.; Drossel, W.-G. A comprehensive comparison of state-of-the-art manufacturing methods for fuel cell bipolar plates including anticipated future industry trends. Journal of Manufacturing Processes 2020, 60, 366–383. Available under: https://doi.org/10.1016/j.jmapro.2020.10.041

4 Verification tests – Provision of stack components based on metallic principal

The decision to use graphite-polymer composite BPPs, instead of metallic BPP, was taken in the first period of the overall research project (decision of the project consortium, in particular the stack manufacturer and the intended end user) [as reported in D1.2].

The main reason for the decision not to focus on metallic BPP was the fact that at that time, due to different framework conditions, the lifetime targets for commercial duty vehicles (such as targeted in the scope of the Fit-4-AMandA project's WP6) could in no case be achieved with metallic BPP. It remains to be seen how this will develop in the future. In principle, scientific research and development is also aiming for much higher life cycle targets for metallic BPP. For this reason, the basic work on the possible implementation of a metallic design was carried out. On this basis, a conversion can be carried out much more easily in the course of the following years after the project has been completed.

Therefore, no functional BPP was designed and implemented to prove the manufacturability of metallic BPPs. Instead, a flow field section was defined which contains significant geometric features of a BPP (basic geometry). A parameter study was carried out on the basis of this basic geometry.

To analyse the MMM (Mass Manufacturing Machine) concept, it was not necessary to test the functionality of the assembly line developed in the project (in WP4) with a functional metallic BPP. The supply, feeding, picking up and manipulation of metallic BPPs can be guaranteed with the system developed for the graphite polymer composite BPPs in MMM. Fundamental changes to the MMM concept in WP4 are not necessary in order to handle and process both types of BPP in this system [9].[7]

For the configuration of the developed machine, an adequately scaled in-line test procedure was initially planned, i.e., a reduced number of cameras for positioning and failure detection (C1 and C2 as shown in Figure 4-1). In the first expansion stage, the automated assembly line was able to handle the following tasks and challenges.

- Handling of either seven-layer MEA or seal-on GDL/CCM was possible without changing the configuration;
- Graphite–polymer composite or metallic bipolar plates stacking;
- At least two stack formats with different cell numbers (with minor adaptions) were producible.

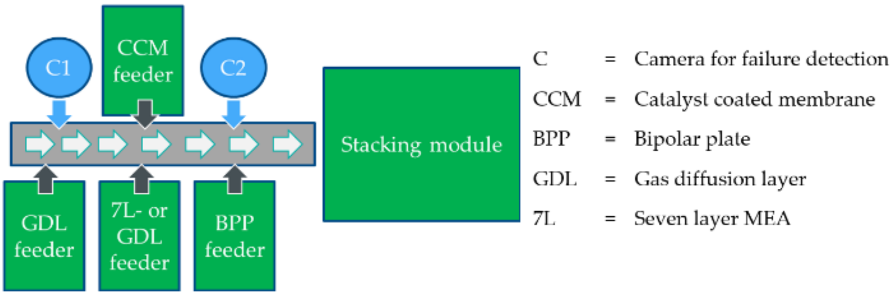

Figure 4-1 Schematic illustration of the modular mass manufacturing machine (MMM) as it is currently built (expansion stage 1) [9].

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[7] Porstmann, S; Wannemacher, T; Richter, T. Overcoming the challenges for a mass manufacturing machine for the assembly of PEMFC stacks. Machines 2019; 7: 1–20. https://doi.org/10.3390/machines7040066.

5 Conclusions & Recommendations

In order to complete the strategy presented here and the results achieved, the following concepts "for test geometries and boundary conditions" are considered in an outlook. The consideration takes place with regard to the determination of a parallel meander-flow field structure producible by forming, by means of a substantially reduced sample size for saving resources with regard to numerical computing times (by reducing the number of elements), size and costs of the test tool, material requirements (test material) and the simplification of the sample preparation due to the correspondingly reduced sample size.

- Concept 1: Blank dimensions 35 mm x 55 mm
- Concept 2: Blank dimensions 75 mm x 55 mm
- Concept 3: Blank dimensions 35 mm x 55 mm combined with 4 constrains
- Concept 4: Blank dimensions 75 mm x 55 mm combined with 4 constrains
- Concept 5: Blank dimensions 35 mm x 55 mm combined with constrains (theoretical consideration)

On the other hand, the possibility of combining a circumferential sealing or blocking groove with artificial boundaries (constrains) was not considered.

Concept 3 and concept 4 are similar to concept 1 and concept 2, but differ from them by an additional locking bead and sealing groove, respectively. Concepts 3 and 4, on the other hand, differ only in the width of the board used.

The achieved results are included in the confidential report D2.4.

Graphitic vs. metallic Bipolar Plate technology

The work performed within the Fit-4-AMandA project focused on the graphite-polymer composite BPPs. The major reason for this decision can be found in the target application, which is a duty vehicle[8]. The specific requirements of this vehicle type/application prefers the chosen technology[9] for several aspects such as:

1. Endurance/Lifetime

For mobile automotive applications of PEMFC stacks relatively low service life requirements of approximately 5.000 to 8.000 operating hours are required. In opposite to this, duty vehicles such as long haul, trucks, communal vehicles buses etc. require service lives of approximately 20,000 to 40,000 operating hours or even more. Furthermore, stationary, rail and maritime applications demand lifetimes in that range, too.

An extensive literature research always referenced sources that state that composite graphite BPPs are superior to metallic BPPs in terms of durability and resistance. This was also one of the main aspects of PM focusing on composite graphite BPPs in their applications.

2. Technical performances

As the target application is a hybridised system with batteries in terms of a “range extender” the fuel cell system has not the high power demands as a full traction FCS. A fuel cell power of 30 to 45 kW is totally sufficient to serve the average power demand while peak demands are covered by the battery.

The performance of the BPP depends on the one hand on the conductivity and on the other hand on the realisable flow field structure. Furthermore, the thickness of the BPP determines how high the stack is ultimately built. In the latter case, the composite graphite BPPs are currently inferior to the metallic ones. But in case of duty vehicles the space limitation is not as drastic as it is in passenger cars.

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[8] *For various internal reasons, this solution was no longer available during the course of the project. Therefore, a refuse collection vehicle from the company E-Trucks was chosen as the application platform.*

[9] Porstmann, S; Wannemacher, T; Richter, T. Overcoming the challenges for a mass manufacturing machine for the assembly of PEMFC stacks. Machines 2019; 7: 1–20. https://doi.org/10.3390/machines7040066.

3. Cost situation

The costs are very difficult to evaluate. But in terms of the described lower power demand, the costs of the total FCS are significantly lower, too. Moreover, battery costs and operational costs (fuel electrical energy) have to be taken in account for the TCO, too. This is not trivial task. From the point of view, it is rather the availability that is critical, since the manufacturing processes for BPPs made of composite graphite materials are inferior to those for metallic BPPs. At least for sheet sizes in the range of DIN A4 and upwards.

4. Production rates

Even though metallic bipolar plates can be manufactured more easily in relatively high production rates and thus in automotive mass volumes, the market volume of commercial applications (preferably stationary, such as for rail-bound and maritime markets) is still considerable. The composite graphite BPPs will continue to be of great importance for these markets in particular.

The question of choosing the appropriate BPP technology is highly dependent on the general circumstances and must always be re-examined and re-evaluated in light of current and ongoing technological progress.

For this reason, the decision to keep the MMM variable and flexible for different stack construction, MEA and, above all, BPP concepts, is a good basis for being able to produce fuel cell stacks in the future, even if the general conditions change.

For this reason, the Fit-4-AMandA consortium strongly recommends keeping an eye on the respective political, social and technological framework conditions and conscientiously following technical progress. This should then lead to a passed strategy for the manufacturing methods of the stacks and their core components at an early stage. This is imperative not only for Proton Motor, but also for all other operational project partners.

6 Risk Register

Risk No.	What is the risk	Probability of risk occurrence[10]	Effect of risk[11]	Solutions to overcome the risk
1	Political climate is changing towards fuel cells	2	2	Constant observation of the current market development and of the political climate
2	Competition with earlier market-ready solutions	2	2	Striving for more cost-effective production, supported by ongoing developments to reduce costs
3	Lack of demand for FC components	2	2	Constant observation of the current market development
4	Confusing overall PEM FC market	2	3	Constant observation of the current market development
5	High investment costs	2	2	Development of alternative approaches for solutions
6	High technical risk	2	2	Development of alternative approaches for solutions
7	High manufacturing costs	3	3	Striving for more cost-effective production, supported by ongoing developments to reduce costs

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

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

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Project partners:

#	Partner	Partner Full Name
1	UNR	Uniresearch BV
2	PM	Proton Motor Fuel Cell GmbH
3	IRD	IRD Fuel Cells A/S
4	Aumann	Aumann Limbach-Oberfrohna GmbH
5	Fraunhofer	Fraunhofer gesellschaft zur foerderung der angewandten forschung E.V.
6	TUC	Technische Universitaet Chemnitz
7	UPS	UPS Europe SA

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Appendix A – Quality Assurance

The following questions should be answered by all reviewers (WP Leader, peer reviewer 1, peer reviewer 2 and the technical coordinator) as part of the Quality Assurance Procedure. Questions answered with NO should be motivated. The author will then make an updated version of the Deliverable. When all reviewers have answered all questions with YES, only then the Deliverable can be submitted to the FCH JU.
NOTE: For public documents this Quality Assurance part will be removed before publication.

Question	Technical Coordinator	Project Coordinator
	Thomas Wannemacher	**Anna Molinari**
1. Do you accept this deliverable as it is?	yes	yes
2. Is the deliverable completely ready (or are any changes required)?	yes	yes
3. Does this deliverable correspond to the DoW?	yes	yes
4. Is the Deliverable in line with the Fit-4-AMandA objectives?	yes	yes
a. WP Objectives?	yes	yes
b. Task Objectives?	yes	yes
5. Is the technical quality sufficient?	yes	yes