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Technology assessment for the joining connections of the flat membrane humidifier

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Abstract

This paper presents a comprehensive technology assessment for the joining connections of the flat membrane humidifier. The goal of this technology assessment is to analyse and evaluate specific technologies for an efficient integration into the flat membrane humidifier manufacturing. The investigations spanned various levels. At the idea level, proposals for design changes were developed and technology-relevant fields determined. Subsequently a technology screening was conducted to identify the most fitting technologies. The technologies were tested in feasibility studies. The results of the comparative analysis are intended identify promising approaches, which were subsequently evaluated with regard to their practical implementation. The feasibility studies and their evaluation provide in-depth insights into the optimal technologies for effective joining connections in the context of the flat membrane humidifier. The results of this study should find application in the flat membrane humidifier manufacture for the automotive supply sector. This research contributes to enhancing the performance and integration of these technologies in practice.

Keywords

Polymer Electrolyte Membrane (PEM) Fuel Cells; humidifier membrane; automotive industry; joining technology; technology assessment

1. Introduction

Proton-exchange membrane fuel cells (PEMFC) have emerged as clean power sources with broad applications. In PEMFCs, chemical energy is converted to electrical energy through an electrochemical reaction, primarily utilizing hydrogen as fuel. Maintaining optimal humidity levels within the fuel cell is crucial to ensure efficient and stable performance.

In recent years, flat membrane humidifiers have gathered significant attention as effective solutions for humidifying reactant gases in fuel cells. Higher humidity levels in the fuel cell lead to increased efficiency and an extended service life. The membrane humidifier is connected directly to the fuel cell. Its function is to separate outgoing and incoming air and pass the humidity of the outgoing air to the incoming air. [1] The automotive supplier Mahle developed a *flat membrane humidifier*. In contrast to conventional membrane humidifier, that use hollow membrane fibres, the flat membrane humidifier consists of various layers of alternating thin membranes and spacers. [2] The layers need to be joined (Figure 1). Currently there is no mass manufacturing line with defined technology process in places since the development of the flat membrane humidifier as product is new. The development of a manufacturing process for the mass production of flat membrane humidifiers was the goal of a publicly funded research project. So as state of the art, it was not possible to resort to previous applied manufacturing processes, and product development is done simultaneously to the technology assessment process. Therefore, proposing product changes at the idea level was possible.

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In the preliminary stage of this technology assessment, a product analysis was conducted where relevant product information essential for the technology selection was gathered and weighted. Additionally, the various functional elements of the product were dissected, and requirements were defined.The core requirements defined for the connecting element were as follows:

- Gas tightness: To ensure that the function of the flat membrane humidifier is given, the joining connection has to prevent any leakages between the airflows. Leakages in the joining zones would lead to a dysfunctional fuel cell system.
- Durability: A differential pressure occurs between the two airflows. The joining connection must be able to withstand small hydrogen-oxygen explosions.
- Material limitations: Due to the materials used (see chapter 2), the permissible temperature in the manufacturing process is up to 120°C.
- Temperature resistance: The connecting element should be capable of withstanding temperatures encountered during operation of about 100 °C without degradation.
- Contamination: The use of technologies that would lead to contaminations or ion ingress is not permitted.
- Automation option: A high level of automation is required for unmanned production with a low cycle time.

The listed requirements were results from previous work packages and are regarded as inputs for the technology assessment.

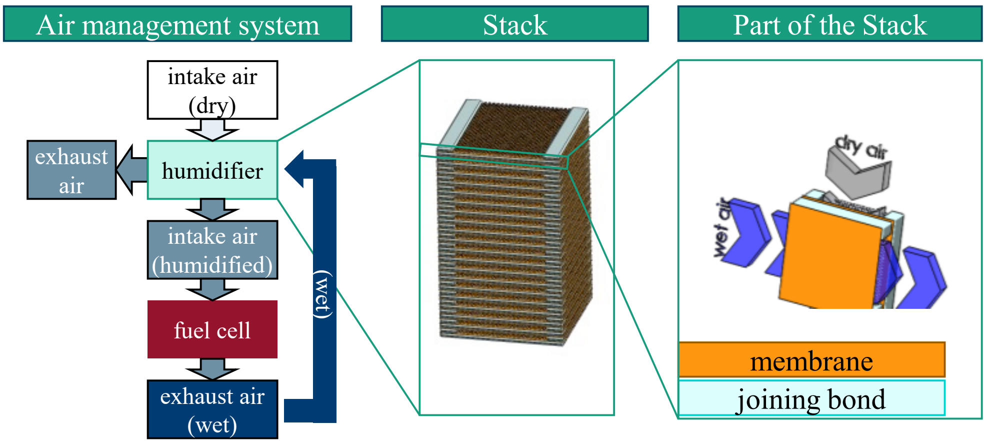


Figure 1: Stack for a flat membrane humidifier of a fuel cell system [1]

The paper shows the methodology and the results of the technology assessment to find the most suitable joining technology for the manufacturing of flat membrane humidifiers. In Chapter 2, the given material is explained to gain a basic understanding of the following steps in the technology screening process. Subsequently, the methodology is described for the technology assessment. The state of the art is depicted in Chapter 4 to set the technology screening in the context of the material used. Furthermore, the different possible joining technologies are described, and the results of the technology screening are shown. Consequently, the most suitable technologies are given, which are further researched in the feasibility study. The results of the feasibility studies are described in Chapter 5 and subsequently discussed in Chapter 6. Showing the theoretical methodology combined with a practical approach demonstrates how a technology assessment can be conducted in other scientific fields. This paper also presents the results of the technology assessment, which can be applied in similar application areas.

2. Material

Perfluorosulfonic acid (PFSA) membranes are considered the standard in PEMFC applications due to their superior thermal, mechanical, and chemical stability, as well as high proton conductivity [3]. This paper focuses on the production of a flat membrane humidifier by using a PFSA membrane as the active layer between the inlet and outlet airstreams. PFSA-based membranes are well-known for their exceptional water conduction properties. To enhance specific properties, such as mechanical strength and stability, the membrane is reinforced and built up as a "sandwich membrane". Additional materials for PFSA membranes are non-woven materials. Non-woven materials are porous substrates that result in a higher membrane lifetime. [4] The membrane used in this paper is a sandwich membrane consisting of a non-woven reinforcement layer on the outside (Figure 2 A). Figure 2 shows a membrane-spacer pouch's profile and the joint.

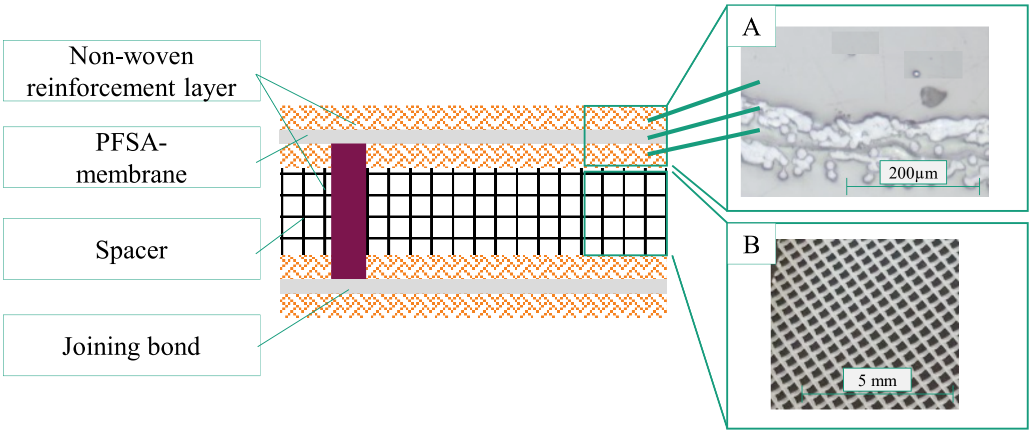


Figure 2: A schematic representation of a spacer membrane pouch.

To facilitate the airflow between the PFSA membranes, a plastic spacer is employed, akin to its use in other systems like energy recovery ventilators or enthalpy exchangers. [5] This spacer features a grid pattern with filaments of varying heights, enabling the airflow to smoothly traverse between the membranes (Figure 2 B). The spacer's thickness can range from 0.5 mm to 2 mm, depending on the specific application. Furthermore, the geometry of the spacer and the thickness of its filaments influence the pressure loss of the membrane humidifier. [5] The spacer is made of polypropylene (PP).

To enable a leakage-free joint connection, a joining technology has to fill the gap between the spacer's grids as well as the pores of the membrane's non-woven material. Additionally, the bond must be strong enough to withstand the pressure of small hydrogen-oxygen explosions. Another challenging aspect was joining uneven surfaces caused by the spacer's grid structure and the membrane's non-woven layer.

3. Methodology

Analogous to the technology calendar method proposed by Eversheim [6], a holistic approach was chosen in the project to identify suitable manufacturing and material technologies and evaluate their potential (Figure 11). During the initial phase of *product analysis*, all properties and interfaces of the product relevant to manufacturing are captured and documented. This stage involves describing the product, including its purpose, features, and influences on the target market. The core requirements are described in Chapter 1.

Secondly, at the *idea level*, brainstorming sessions are conducted to generate innovative solutions and concepts. During idea generation, flexibility is allowed to address design changes that may grant for better utilization of technology. In addition, relevant search fields are identified, which could be suitable sources of ideas for technologies and technological solutions. (For instance, a Cell Battery Stacking Machine could meet similar requirements, as it has a highly automated stacking process.)

A *technology screening* explores potential usable technologies based on the ideas generated. Experts in current research fields are interviewed to represent new manufacturing technologies. A segment from the technology screening is presented in the state of the art. In order to develop the most promising technologies further, *feasibility studies* are performed. Prototyping, testing, and risk analysis are conducted to evaluate the feasibility of proposed solutions. A leakage test based on pressure loss was carried out to test the different technologies. In this test, prototypes of membrane pouches were created and tested under a pressure of 2 bar.

Relationships with other process steps from various individual processes are not presented in this paper but are represented in the overall project approach. At the end, an evaluation of the approaches is conducted to identify the most promising technologies. In this paper, a preliminary cost-benefit analysis is performed to provide an outlook on the most suitable joining technologies.

4. State of the Art – Technology Screening

The goal of the paper is to find the most suitable technology for joining a spacer and membrane. Therefore, possible joining technologies were inspected in the technology screening. As guidance, DIN 8580 and DIN 8593 are referred to, which summarize various joining technologies. The most significant limitations to select a method during the screening process are the material constraints, automation feasibility, gas tightness, and the product design enabling crossflow.

According to DIN 8580, joining refers to the permanent joining of two or more workpieces with a geometrically defined shape or the bringing together of workpieces with a shapeless material, whereby cohesion is created and increased as a whole. [7]

DIN 8593 defines various groups for joining, including filling, pressing on and pressing in, joining by master forming, joining by shaping, joining by welding, joining by soldering, and adhesive bonding. [8] The result of the screening process is shown in Figure 3.

Casting processes as part of processes for *joining by master forming* are, for example, used in medical products to produce membranes with microchannels. These microchannels serve to selectively separate different substances. At the idea level, this was considered an intriguing concept. However, no suitable partner for further development of the technology was found during the technology research, thus leading to its abandonment. [9]

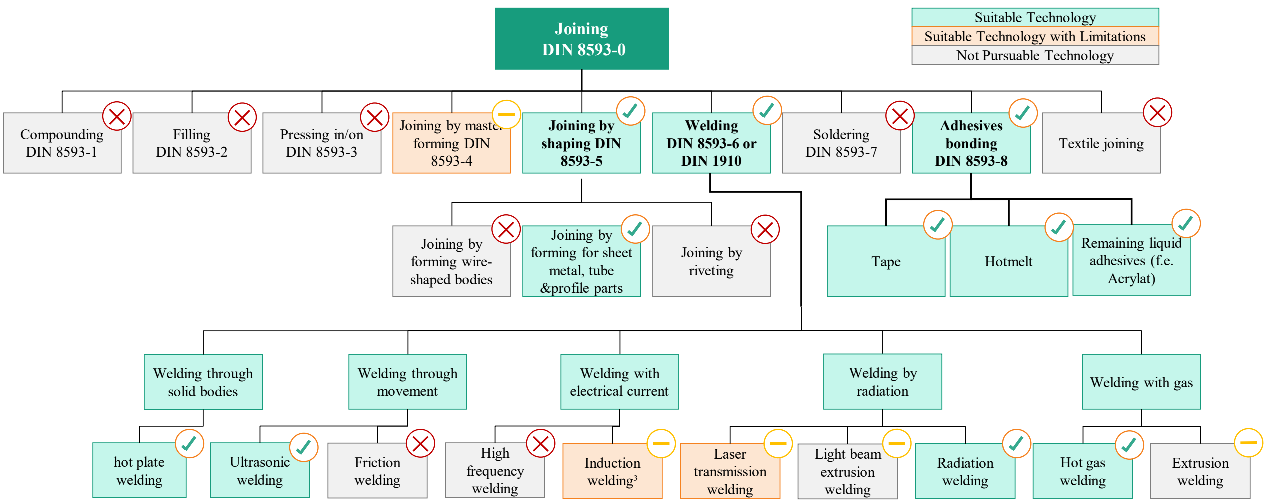


Figure 3: Relevant technologies systematically presented according to DIN 8593 [8]

Mainly, different kinds of *welding processes* would be applicable to achieve the joining connection. In contrast, *friction welding* is not suitable for films or foils due to the high forces involved and the necessity to precisely control the movement of the parts being joined. *High frequency welding* can only be applied to polar materials such as soft and hard PVC, polyurethane (TPU), certain polyamides (PA), certain polyesters

(PES). Since the materials used for the flat membrane humidifier are not polar and cannot be polarized, high frequency welding cannot be used. *Extrusion welding* and *light beam extrusion welding* introduce additional material during the welding process. Since the advantage over adhesive bonding is not present in this case, adhesive bonding may be preferred as it offers a stronger adhesive connection between the membranes.

Heating by thermal contact, also known as *hot plate welding* is the most commonly used process for joining thin packaging materials. *Hot plate welding* can be applied to a wide range of thermoplastic materials. This versatility makes it suitable for diverse applications across various industries [10].

Ultrasonic welding was also considered a viable option [11]; however, it was not utilized in this paper due to the elaboration and development being carried out by partners.

Induction welding and sealing are being developed for packaging materials with a corresponding composite structure, offering numerous advantages over traditional heat contact sealing methods. These advantages include significantly higher energy efficiency, targeted and effective heat input close to the point of action, and enhanced product protection through precise control of heat input. Additionally, the short control cycles of induction sealing increase efficiency and productivity. However, for the sealing of food packaging, the unique dynamics of inductive heating of thin layers pose new challenges and demands on the packaging material to ensure optimal performance and safety. [12]

In the case of *laser transmission welding*, the optical properties of the materials being welded play a crucial role in the welding process. One significant challenge arises when the materials are transparent; thus, an energy deposition in the welding area is impossible. This problem becomes particularly pronounced when welding materials with similar optical properties. Infrared absorbers are commonly applied to the absorbing joining partner to address these challenges. The infrared absorbers can be introduced as an additive incorporated into the plastic meld or applied as a coating directly onto the surface layer between the welding partners. This approach allows for effective energy absorption in the laser's chosen wavelength range while maintaining the transparency of the welded components. [13]

When looking towards an automation process, *radiation welding* and *hot gas welding* face challenges similar to those faced by *hot plate welding* during implementation. These processes involve melting the materials and then bonding them under specific pressure. One-sided accessibility must be ensured, and other layers must not be excessively heated. *Radiation welding* requires additional consideration of material absorption. Due to the shared challenges and transferability of the feasibility study results, we decided to focus solely on *hot plate welding* instead of *radiation* and *hot gas welding*.

Adhesive bonding involves bonding two surfaces together using an adhesive. *Tape* is a thin, flexible material with adhesive on one or both sides, offering convenience and ease of use for temporary fixes. *Hot melt* glue is solid at room temperature and requires heating to become liquid, thus providing quick and strong bonding for various materials. *Liquid glue*, remaining in liquid form until it dries, offers versatility and strong adhesion but may take longer to cure than hot-melt glue. Each adhesive type serves different purposes, catering to various bonding needs in crafts, repairs, and construction.

Additionally, folding, classified as a *forming process* according to DIN 8930, was investigated. It is frequently used in the manufacturing of batteries. In this process, the separator's meandering, planar structure is created through sequential folding using linear motion or rotation with a maximum rotation angle of 180°. The assembly can be formed by a continuous separator tape that encloses the entire cell assembly with at least one fold encompassing the electrode material. [14,15] Folding with a joining method applies to flat membrane humidifier manufacturing.

When exploring various joining technologies and considering existing ideas, it becomes apparent that we can differentiate between through bonding and single-sided bonding. The first one is only applicable for manufacturing membrane-spacer pouches, while the latter is also a suitable method for building up the stack.

Through bonding involves arranging the materials on top of each other and subsequently joining them, which can be problematic when layers underneath should not be joined. On the other hand, single-sided bonding is applied to the bonding partners first, and joining is the second step, while it only affects the bonding partners' surfaces facing each other (Figure 4). The differentiation helps in the evaluation of the technologies.

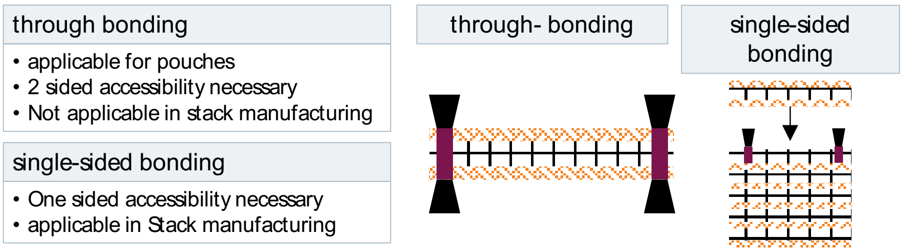


Figure 4: Illustration of the difference between through bonding and single-sided bonding

The outcome of the technology screening is to focus on the following technologies for the feasibility studies: folding, hot plate welding, induction welding, laser transmission welding, and adhesive bonding.

5. Results

The paper first addresses the most relevant ideas for optimizing the product by changing its design structure. Next, it will explain the preliminary results regarding the feasibility and technological screening. Figure 5 shows possible product adjustments and illustrates potential alterations to the structure.

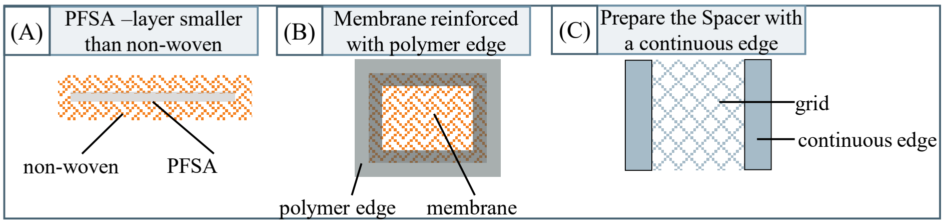
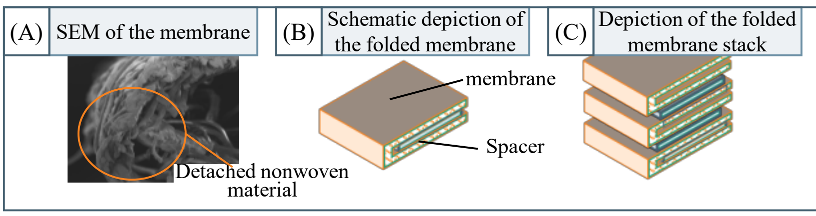


Figure 5: Possible product changes based on the idea generated

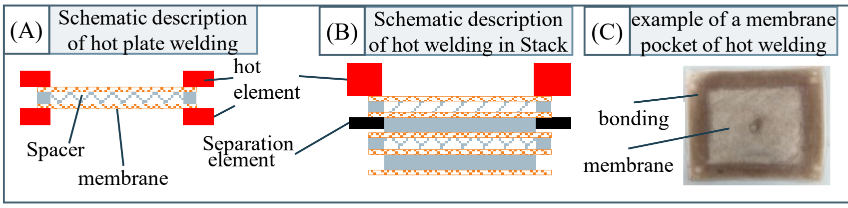
One possible design change to improve the applicability of technologies is to change the manufacturing process so that the nonwoven material's surface area is bigger than that of the impenetrable PFSA layer. (Figure 5 A) With an approach like this, a joining technology that penetrates through the porous non-woven material can be used. It would also be advantageous that it would not be necessary to integrate PFSA in the joining bonding. Another idea is to reinforce the membrane with a polymer edge by an additional welding process such as hotplate welding. (Figure 5 B) It could also be done by 2K injection molding, finding applications in the automotive or healthcare industries. [16] With this approach, the sandwich membrane would be protected against delamination, and it would be possible to use the same polymer as used for the spacer, making it easier to weld together. The third proposed idea in this paper is to construct a spacer with continuous edges on two sides. (Figure 5 C) It would allow for the use of another joining technology because it would eliminate the problem of filling the grid holes and would not cause issues with height differences.



folding	
Pressure loss (bar)	0,02
Cycle time (2 sided)(sec)	1
Cycle time (1 sided)(sec)	1

Figure 6: Investigation towards a folding membrane stack concept.

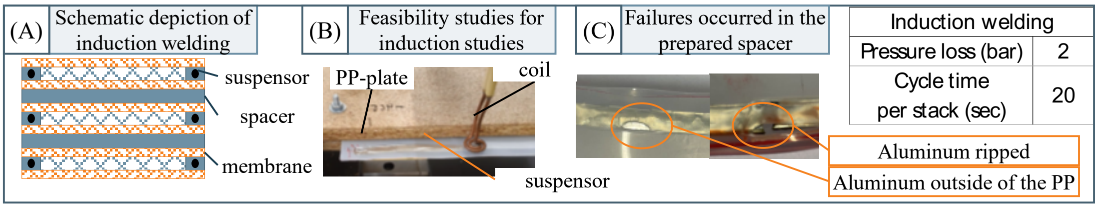
As mentioned in the state-of-the-art, in battery manufacturing systems, Z-**folding** is used to separate anodes and cathodes. The separator consists of a continuous material web. In this case, the sheets of the anode and cathode are initially cut and then inserted into the separator. A continuous material web keeps the two electrodes separated via a Z-folding process. [14,15] Analogously, similar approaches could be employed to assemble the flat membrane humidifier continuously. Here, the membrane would be folded (Figure 6 BFigure 6). However, at the idea level, no straightforward solution was found to maintain a continuous membrane and the crossflow of the air simultaneously. Therefore, only the idea of folding one side and bonding the other to build a pouch was forwarded. (Figure 6 C) The folding was optically examined in detail, and leakage tests were conducted by sealing off all other sides. It was observed that the folding did not create any leakages, and no optical defect was noted. However, it was noticed upon closer examination that the nonwoven material detaches from the PFSA-membrane at the inner fold. (Figure 6 Figure 6A)



hot plate welding	
Pressure loss (bar)	0,02
Cycle time (2 sided)(sec)	5
Cycle time (1 sided)(sec)	20

Figure 7: Investigation towards a hot plate welding concept

Hot plate welding can be used with one or two hot elements (Figure 7). [17] Hot plate welding for creating through bonding can be achieved with two hot plates from both sides. (Figure 7 A) This has the advantages of symmetrical bonding and a faster heating process. Hot welding within the stack must operate with only one hot element and a separation element to avoid welding the layers underneath (Figure 7 B). We produced a membrane pouch to test the method's feasibility. (Figure 7 C). While cycle times for a one-sided joining are about 20 seconds, two-sided joining cycle times decrease to 5 seconds at 240°C. An optical change of the membrane was also noted, which could not be attributed to changes in the product function.



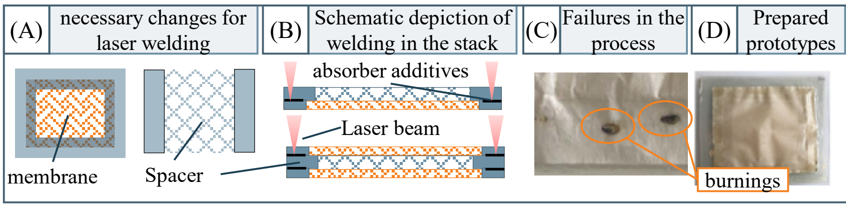
Induction welding	
Pressure loss (bar)	2
Cycle time per stack (sec)	20

Figure 8: Investigation towards an induction welding concept.

Induction welding is a process that does not require any physical contact between the induction coil and the heat susceptor. It is possible to design it to ensure that heat only builds up within the desired weld area (Figure 8). Susceptors typically consist of metallic powder in an interspersed form or the form of a powder or mesh, and play a crucial role in this process. [18] One advantage of this technique is that it allows for stacking the stack and then welding the entire assembly at once using a coil. (Figure 8 A)

We used two types of coils for the feasibility studies. One was a short-wavelength coil using 700 Hz and 0,5 - 1 kW and the other was a long-wavelength coil using 20 Hz and 0,7 - 1,9 kW to heat the foil. The long wavelength would be more applicable as it would reach deeper into the workpiece. Wire and foil were prepared as suspensors. They were incorporated into the continuous plastic plates. (Figure 8 B) It was observed that using foil resulted in a more stable process. Nevertheless, while it was possible to heat the material, it was found to be unstable. Additionally, it took work to ensure uniformity throughout the process, as the aluminum melted out of the PP in some areas. (Figure 8 C) In contrast, in other areas, it did not melt properly or the aluminum foil ripped during the welding process.

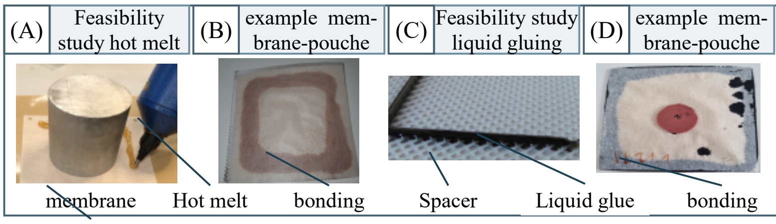
Laser welding is commonly used to join plastic components. If both components are transparent, an absorber enhanced by pigments can be used. The energy is absorbed by the pigment, usually a metal, creating heat that forms the welding seam. [13] Incorporating absorber laser welding into the stack allows for versatility in configurations, whether with a spacer above or a membrane above. As a result, the entire stack can be assembled using the laser welding process. (Figure 9 B).



Laser welding	
Pressure loss (bar)	0,43
Cycle time (2 sided)(sec)	1
Cycle time (1 sided)(sec)	1

Figure 9: Investigation towards a laser welding concept

When looking at the flat membrane humidifier initially, the optical characteristics were measured to find the most fitting wavelength. Both optical characteristics of the membrane and the spacer suggested that the wavelength of a CO2 laser (1060 nm) could transfer enough energy between the layers. However, upon checking the first welding result (Figure 9 C) it was noted that laser welding caused burning on the outside of the membrane and did not achieve a uniform weld. Another idea was to modify the spacer and membrane (Figure 9 A). To realise these idea for testing we built membrane with PP-edges using hot plate welding with 0.1mm thick foils. The foils were welded on the edges of the membrane. These membranes were then welded together with a spacer with continuous edges by applying laser welding resulting in membrane pouches (Figure 9 B). The resulting membrane pouches showed good optical membrane properties. However, after leakage testing, it was found that the membrane did not hold enough pressure and broke at 0.3 bar.



	Hot melt	Liquid gluing
Pressure loss (bar)	0,05	0,02
Cycle time (2 sided)(sec)	8	6
Cycle time (1 sided)(sec)	8	6

Figure 10: Investigation towards a glue concentrated concept

Adhesives are already being utilized to seal bonds in fuel cells. Here, adhesives not only serve the function of bonding but also act as sealants. [19] Researching suitable adhesives was challenging since many adhesives are contaminative by washout effects. Tapes, hot melt adhesives, and liquid adhesives were examined to establish a tight bond in the flat membrane humidifier. During the research there was no *tape* found which could fill the non-woven material and create a gas-tight connection. *Hot-melt* adhesives have a high viscosity, which poses challenges during application to the membrane. Consequently, the adhesive was applied to the membrane, and the spacer and the second membrane were pressed on. (Figure 10 A) However, it was observed that with sole adhesive application, the second membrane was not completely wetted, necessitating another heating process The *liquid adhesives* available had a lower viscosity. Thus, the membrane and spacer were first placed, followed by adhesive application (Figure 10 C). The whole assembly then underwent further curing in the oven. Tight membrane-spacer pouches could be created through adhesive bonding.

6. Discussion

In this discussion, the different presented technologies are compared and evaluated. The summary of the evaluation is summarized in Table 1. The design changes of the product are not evaluated individually but are included in the evaluation together with the technologies. In the following, the evaluation of the different technologies is explained.

In the processes of *induction welding* and *laser welding*, a gas-tight pouch could not be produced. Both technologies hold promise for economical potential in manufacturing flat membrane humidifiers. Despite the effort invested in prototype development, a gas-tight pouch could not be achieved within this project. More time needs to be invested in process development, which was not feasible within the scope of this project. Overall, induction welding of films is still in the developmental stage, making it likely that a positive outcome with laser welding could be easier to achieve. However, due to the economic risk involved, further pursuit of both technologies has been discontinued.

Folding has been used to create gas-tight pockets. However, no method has been developed to exclusively produce a membrane stack through folding alone, as this does not generate cross-flow. Folding can thus only be utilized as a substitute for a connection in the through connection. In the further development of the process, there is also the question of whether the material is additionally weakened by folding. Repeated folding can lead to material fatigue and weakening, especially in materials with low elasticity or breaking strength. Nevertheless, additional technology for the non-folded side must be utilized regardless. Since it is only feasible for one side, it would not replace the use of a technology, and due to the risk of material weakening, further attempts are not warranted.

With *hot plate welding* technology, a gas-tight membrane could be created. It's cost-effective doesn't require foreign materials, but the material must briefly reach 230 degrees Celsius, which shouldn't have any adverse effects on it. However, in hot welding within the stack, there's a risk of heat influencing the layers. So there has to be more development effort. For the cycle time per layer, it was measured at 20 seconds per layer. When looking at a two-sided approach for the thorough connection, the cycle time could be around 10 seconds. Another advantage of hot welding is that no additional material costs have to be considered. Height differences in the stack can arise from melting the plastics and applying pressure.

The other efficient technology is the use of adhesive bonding. Here, although tight pockets could be produced. In contrast to hot welding, additional material can be added through the mass of the adhesive, and no height difference needs to be determined. When looking at hot melt, it is noteworthy that a re-compacting must take place. This means that when looking at a stack, the entire stack is heated to a temperature of 120°C and then compressed. This means that the material must be above the originally intended maximum temperature for a while. When looking at liquid adhesive bonding, it is inevitable that the disadvantages are the curing of the adhesive after production and the cost of the adhesive.

Because of the limited project frame and time for process development, it seems most sensible to proceed from the technology screening to using a hot melting technology for throughput and adhesive bonding for stack integration.

7. Conclusion

The objective of this paper was to demonstrate the methodology along with the results obtained from various methods aimed at establishing a connection for the flat membrane humidifier. Through this approach, two promising methods were identified for further investigation: induction welding and laser welding, both exhibiting considerable economic potential. These processes can be further developed in subsequent research endeavors to achieve a functional combination of membrane spacers. Furthermore, hot welding and gluing were selected as dual-functional alternatives for further progress. Gluing offers higher process reliability, whereas hot welding proves to be more cost-effective and potentially equally reliable. However, the potential risks associated with hot welding within the stack warrant further exploration. Hence, based on technological assessment, it is recommended to employ hot welding for the preparation of membrane spacers and gluing for integration within the stack.

Acknowledgements

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Appendix

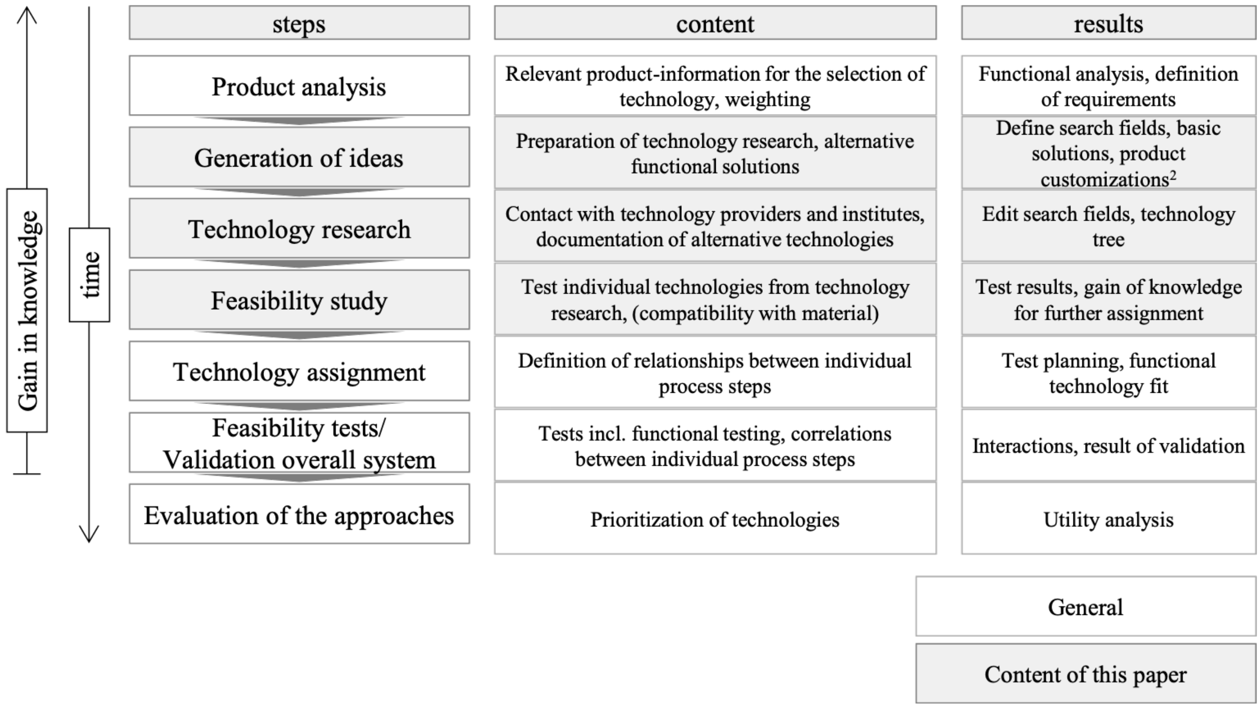

Figure 11: methodology technology assessment

Table 1: Evaluation of the technologies

	Table	Induction Welding	Laser Welding	Folding	Hot welding	Adhesive liquid glue	Adhesive hot melt
Basic requirements	Gas Tightness	-	-	++	++	++	++
	Durability			*Risk*			
	Material limitations				*Risk*		*Risk*
	Contamination	-	-				
Performance requirements	TRL - Level	low	high	high	high	high	high
	Development effort	high	high	low	Low for through connection/medium for single joint	low	low
	Automatability	high	high	high	high	high	high
	Cycle time	20 sec per stack	1s per layer	1 sec per layer	20 sec per layer	6 sec per layer	8 sec per layer
	Additional material costs	yes	yes	non	non	yes	yes

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