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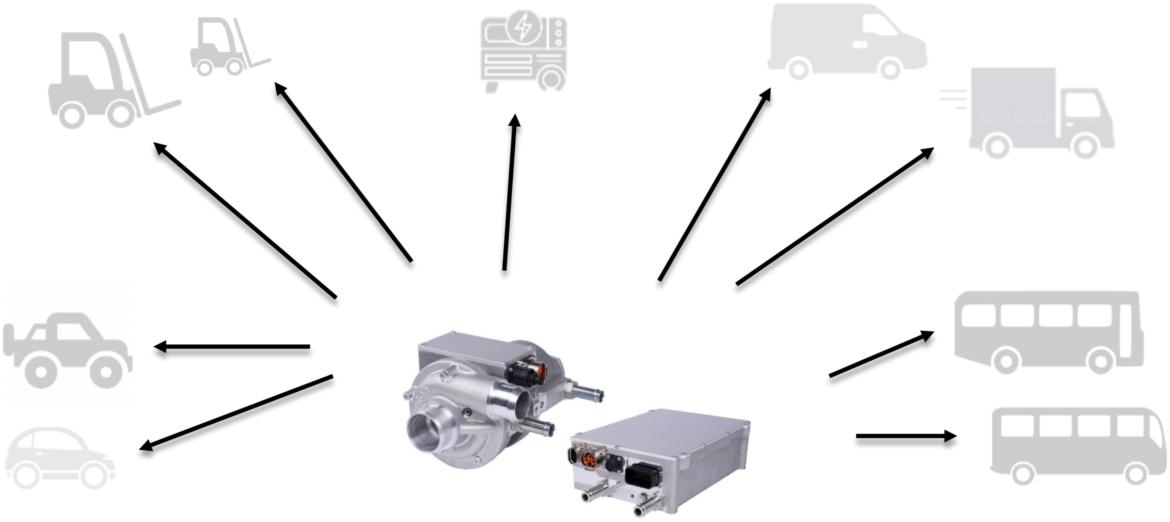
Final Report

COMBLOC

Compressor system building blocks



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Summary

Fuel cells for mobile application such as passenger cars, commercial vehicles (for lifts, delivery vans, trucks, buses) and train applications require an air supply with a compressor. Due to the dynamic market and technology development there is no clear standardization in the compressor specifications yet. This project targets to solve this problem by a smart combination of compressor system building blocks for different specifications. This allows for compressor systems with lower cost and lower validation effort than fully application specific compressor systems, and higher efficiency than existing, but non-optimal compressor systems. The research results from this project allow the fuel research and development community to improve efficiency and reduce cost, and with this strengthen the fuel cell technology and market acceptance.

Zusammenfassung

Brennstoffzellen für mobile Anwendungen wie PKWs, Nutzfahrzeuge (für Aufzüge, Lieferwagen, LKWs, Busse) und Zuganwendungen benötigen eine Luftversorgung mit einem Kompressor. Aufgrund der dynamischen Markt- und Technologieentwicklung gibt es noch keine klare Standardisierung der Kompressorspezifikationen. Dieses Projekt zielt darauf ab, dieses Problem durch eine intelligente Kombination von Kompressorsystem-Bausteinen für verschiedene Spezifikationen zu lösen. Dies ermöglicht Kompressorsysteme mit geringeren Kosten und geringerem Bewertungsaufwand als vollständig anwendungsspezifische Kompressorsysteme und eine höhere Effizienz als bestehende, aber nicht optimale Kompressorsysteme. Die Forschungsergebnisse aus diesem Projekt ermöglichen es der Brennstoffzellen-Forschungs- und Entwicklungsgemeinschaft, die Effizienz zu verbessern und die Kosten zu senken und damit die Brennstoffzellentechnologie und die Marktakzeptanz zu stärken.

Résumé

Les piles à combustible pour les applications mobiles telles que les voitures, les véhicules commerciaux (pour les ascenseurs, les camionnettes, les camions, les bus) et les applications de train nécessitent une alimentation en air avec un compresseur. En raison du développement dynamique du marché et de la technologie, il n'existe pas encore de standardisation claire des spécifications des compresseurs. Ce projet vise à résoudre ce problème en combinant intelligemment des modules de systèmes de compresseurs pour différentes spécifications. Cela permettra d'obtenir des systèmes de compresseurs moins coûteux et moins difficiles à évaluer que les systèmes de compresseurs entièrement spécifiques à une application, et plus efficaces que les systèmes de compresseurs existants mais non optimaux. Les résultats de ce projet devraient permettre à la communauté de recherche et développement sur les piles à combustible d'améliorer l'efficacité et de réduire les coûts, renforçant ainsi la technologie des piles à combustible et son acceptation par le marché.

Main findings

Specifications in the fuel cell industry will stay dynamic, standardization concerning power classes, voltage levels, pressure/flow requirements, ambient conditions and many more requirements is coming, but more slowly than expected and forecasted. Fuel cell components, specifically a compressor system based on building blocks that can be adapted for different specifications, are mandatory for the next years to allow for the fuel cell market to evolve. For the H2-community it is important to assess which fuel cell system requirements have become a standard, and therefore also component requirements can be fixed, and which fuel cell system requirements are still evolving and therefore have to be covered with flexible designs such as building blocks and/or modular approaches.

This project shows that the maximum range of fuel cell power classes that can be covered with only modifying building blocks in a baseline compressor, and limiting the compressor efficiency reduction to 5%, is around 40-100%, i.e. with the investigated baseline compressor as of this project a range in fuel cell power class from 25 to 60 kW. A baseline compressor for the next size fuel cell power class according to this finding can cover a range of fuel cell power class from 60 to 150 kW. This is important for the H2-community, specifically for fuel cell system integrators and stack manufacturers, to define their power classes, i.e. such that they can plan to cover a 60-150 kW fuel cell stack/system product line with the same baseline compressor. Since no standardization in pressure ratio and mass flow requirements are present for the different fuel cell power classes, the fuel cell system integrators and stack manufacturers either a) use standard compressors and accept the disadvantages in efficiency and operating range or the compressor, or b) invest into a custom design, or c) now according to this project choose a building block design (with smaller efficiency and operating point range disadvantages than with a), or d) invest (with much smaller duration and cost than with b) into a new building block design.

The input voltage can be adapted without impact on the efficiency, however it requires significant design adaptions and validation. This is in line with the standardization that is happening at fuel cell system integrators in the high-voltage range (with HV2 and HV3 voltage levels), but not yet in line with the still evolving low voltage requirements between 36 and 80 Vdc.

Somewhat surprisingly, a building block design has minimal impact onto the piece price in serial production, therefore, for single applications with large quantities custom designs will remain. However, the design and validation of two such building block system variants further shows that the design and validation effort and therefore cost and time to market is reduced significantly by 46% (for adaption of the input voltage) and up to 91% (for adaption of the aerodynamic building block) when using building block versus full customized compressors systems. Therefore, building block compressor systems therefore give the H2 community a powerful measure to allow for shorter time to market than with full customized compressors systems, especially important for the upcoming years and projects with small to medium quantities.

The main findings of this project can be rolled out to other compressor and fuel cell power levels by Celeroton or other compressor manufacturers, and with adaptions also to other fuel cell components.

Contents

List of abbreviations

DC	Direct current
AC	Alternating current
FEM	Finite element method
rms	Root-mean-squared value
EMF	Electromotive force
Si	Silicon
GaN	Gallium nitride
SiC	Silicon carbide
MOSFET	metal oxide semiconductor field-effect transistor
HEMT	High-electron-mobility transistor
PCB	Printed circuit board
SMD	Surface mounted device
EMI	Electro-magnetic interference

1 Introduction

1.1 Background information and current situation

Hydrogen is identified as one of the key enablers on the journey towards sustainability and a net-zero society. To combat climate change, fuel cells are considered as a key technology to convert hydrogen into electrical power reducing emissions compared to traditional fossil energy and providing advantage compared to batteries and other green technologies.

Today, many fuel cell applications are in development and produced in small- to medium-sized volumes for a large range of applications and power classes. These include forklifts, passenger and commercial vehicles, marine transportation, train, aerospace as well as stationary power generation. Fuel cell power classes are also distributed across applications typically going from 20 kW to 300 kW. Despite some variations across projections; market players expect the fuel cell market to rapidly grow over the next 5 years towards >1 million fuel cells produced annually in 2030.

To achieve high volume deployment of fuel cell technology, preparation for scaling and cost reduction are major priorities the industry has to tackle. Over the past years, most R&D activities have been focused on the fuel cell stacks and not on the balance of plant (BoP) components. The air supply (compressor) is one of the BoP most critical components because of its high impact on the overall system performance (efficiency), design and validation efforts as well as manufacturing and operation costs.

To support the journey and achieve competitiveness against traditional power source, the US Department of Energy (DoE) has defined cost targets for fuel cell systems according to Figure 1.

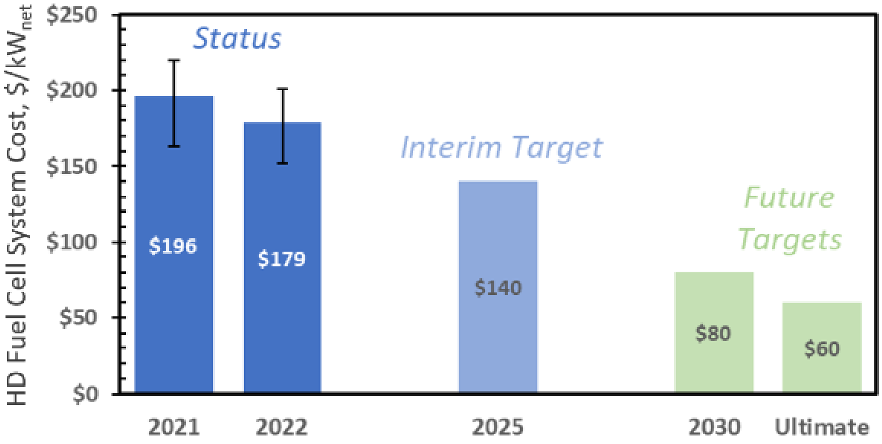


Figure 1: Modeled fuel cell system target costs per kW net power output for 50'000 units per annum in 2025 and 100'000 units per annum in 2030 and beyond. Source: US Department of Energy (DoE)

These metrics are used to derive target fuel cell system costs but also single BoP component costs. For example, a 150 kW fuel cell for a trucking application should reach around 21'000 USD in 2025 (for 50'000 vehicles) and decrease to 12'000 in 2030 (for 100'000 vehicles). The air supply typically ranges between 10-20% of the overall fuel cell cost and would therefore allow for a 2'000-4'000 USD budget in 2025 and 1'000-2'000 USD budget in 2030.

When looking at the compressor market, key players (e.g. Garrett, Bosch, Fischer, Xeca Turbo or Celeroton) are progressively reducing costs but slower than expected while the cost pressure is increasing. One of the main reasons is the large diversity of requirements across applications and the lack of standardization.

Market standards are not yet well defined due to the high fragmentation of the market across applications, players (OEMs, fuel cell system integrators, stack manufacturers) and power classes. Therefore, requirements and specification for fuel cell systems, and more specifically the requirements and specification of the air supply for the fuel cell stack, vary across application area, fuel cell stack provider, fuel cell system integrator, but also based on final customer/OEM. Currently, there is still no clear standardization in the compressor system specifications such as input voltage levels, pressure ratios and mass flows. This will change in future where the larger players will set the standards, but for the intermediate term, the compressor systems have to be somewhat flexible to adapt to the individual specification sets, while at the same time avoiding a fully customized compressor for each application and customer. In lower power fuel cell applications where Celeroton offers a baseline system, specification fragmentation is probably even higher and a challenge towards scalability. More specifically, in the 20-60 kW fuel cell power range, there are various different fuel cell applications, such as fork lifts for material handling, light commercial vehicles, cars, and even range extender for buses. This, together with the individual system architectures of different customers, results in various compressor system specification sets. Examples of such compressor system specification sets for 20-60 kW fuel cell systems are given in Table 1.

					
Application	Fork lift / material handling	Light commercial vehicle customer A	Light commercial vehicle customer B	Car range extender	Bus range extender
Fuel cell power (kW)	20-30	30-45	30	20-30	20-30
Input voltage (Vdc)	<100 (undefined)	230-380 (HV battery)	120-320 (FC output)	250-450 (fuel cell or HV battery)	180-320 600-750 (FC output) or 600-800 (HV battery)
Battery start	Yes	No	Yes	Yes	Yes / No
Pressure ratio (-)	2.3	2.0	2.1	1.9	1.85
Mass flow (g/s)	33	66	50	30	40
Inlet pressure (bara)	0.9-1.04	0.76-1.04	0.76-1.04	0.76-1.04	0.76-1.04
Cooling water temperature	Tbd in project	Tbd in project	Tbd in project	Tbd in project	Tbd in project
Further specifications	Tbd in project	Tbd in project	Tbd in project	Tbd in project	Tbd in project

Table 1: Example of fuel cell compressor specification sets (extended and modified during project).

These different specification sets prohibit economic benefits that come with standardization and economy of scale when components, especially the compressor system, can be reused for different application areas and customers. Furthermore, it often results in suboptimal combination of Balance of Plant (BoP) system components, or the operation of compressor systems outside the optimal operating points, which lowers the overall efficiency and performance of the entire fuel cell system. The standardization cannot be enforced by smaller market players, but has to be coped with until time and big market players set the standards.

To the knowledge of Celeroton, the effect onto fuel cell efficiency of suboptimal combination of BoP system components, specifically the operation of standard compressor in low efficiency working point, has not been researched. Furthermore, no generic solutions for the challenge of non-standardized specifications in the evolving fuel cell market has been an area of research.

1.2 Purpose of the project

This project targets to propose solutions to overcome abovementioned problems, to analyze the effect of these solutions compared to the state-of-the art, and to theoretically and experimentally verify the solutions. The key approach to solve, or mitigate, these problems is to define building blocks (BB) within the compressor system, and reusing as many of the same building blocks as possible for different specification sets. This modularization of a Celeroton base system suited for that power range provides a new approach towards a standardization of air supplies for fuel cell systems and ultimately cost efficiency for the ecosystem. The building blocks are depicted in Figure 3 (compressor building blocks) and Figure 4 (converter building blocks):

- Aerodynamics: If the required operation range or operating points concerning inlet pressure and temperature, pressure ratio and mass flow change significantly, the aerodynamic building block has to change. Currently there is not standardization in stack design, piping design, etc. which would allow to also standardize this operating range, therefore a building block design for the aerodynamics is key until such a standardization is achieved by the fuel cell community.
    - Air bearing: If the required inlet pressure and temperature range changes significantly, the air bearing building block has to be adapted. This can happen in case of mobile applications (high altitude), aerospace applications (even higher altitude) vs. stationary application (limited altitude range). There is a standardization happening per application.
    - Motor (including winding): If the aerodynamics change, the power requirement for the motor changes. Usually the motor is designed for maximum power, and all aerodynamic designs for lower power have an over dimensioned motor, but in some cases it might be required to adapt the full motor to achieve other requirements (such as compatibility with converters or higher efficiency)
    - Motor winding (itself): If the converter input voltage changes, only the converter input stage can be adapted (with integrating a boost leading to drawbacks in efficiency, size, weight and cost of the converter) or the converter input + output stage and the motor winding can be adapted.
- Converter building blocks
    - Converter input stage: If the converter input voltage changes, only the converter input stage can be adapted (with integrating a boost leading to drawbacks in efficiency, size, weight and cost of the converter) or the converter input + output stage and the motor winding can be adapted.

- Converter output stage: If the converter input voltage changes, only the converter input stage can be adapted (with integrating a boost leading to drawbacks in efficiency, size, weight and cost of the converter) or the converter input + output stage and the motor winding can be adapted.
- Firmware: Customer requirements may require to adapt the firmware. This is avoided whenever possible.

1.3 Objectives

The project determines if the proposed solution (building blocks) is effective to resolve the challenge (changing compressor specifications due to an evolving fuel cell market). For this, the building blocks to be adapted compared to the baseline building blocks of an existing baseline compressor system for 45-60 kW fuel cell systems (Celeroton turbo compressor CT-2000 with converter CC-2000, depicted in Figure 2) are identified per specification set.

The compressor system based on building blocks are compared to a custom specific design for the respective specification set concerning the key performance indicators (KPIs) according to Table 2. The comparison values for the custom specific design are based on scaling models. This comparison allows for the selection of specification sets which can be covered by a modular compressor system based on building blocks, and identify specification sets which have to be covered by a custom specific compressor system.

Figure 2: Baseline compressor system for 45-60 kW fuel cell systems: CT-2000 with converter CC-2000.

KPI	Target values / limits for BB compressor vs. custom specific design	Modelling / Verification	Remarks.
Size/weight	+50%	Size/weight scaling models based on existing compressors and converters (size and weight scale proportionally for the same compressor technology)	Upper limit.
Product cost	+10%	Cost models based on existing compressors	Upper limit. Comparison at same quantity 1000, meaning price for 1000 building block designs can be slightly higher than for 1000 custom designs because of e.g. over dimensioned motor, but then for e.g. two or three building block designs manufactured at the same time this should allow for the same or lower overall cost compared to two or three custom designs. Cost reduction by BB compressor shall come via economy of scale, not via product cost at same quantity, therefore there is a slight increase in product cost at same quantity allowed.
Compressor efficiency	-5%	Aerodynamic preliminary designs + efficiency models based on existing compressors and converters	Lower limit.
Fuel cell efficiency / primary energy consumption	-1% / +1%	Simplified fuel cell models	Lower limit / upper limit.
Design and validation effort	-50%	New model to be defined in project	Target value.

Table 2: KPIs and respective target values and limits for the compressor systems based on building blocks.

The theoretical investigations are validated for two building block designs: an adapted aerodynamic building block described in chapter 3.4 and an adapted converter input + output stage and adapted motor winding in chapter 3.5. The validation includes the research and development of certain building block options, specifically a new converter input stage, a new aerodynamics, and an adapted motor winding, and the integration of such new building blocks into the baseline system.

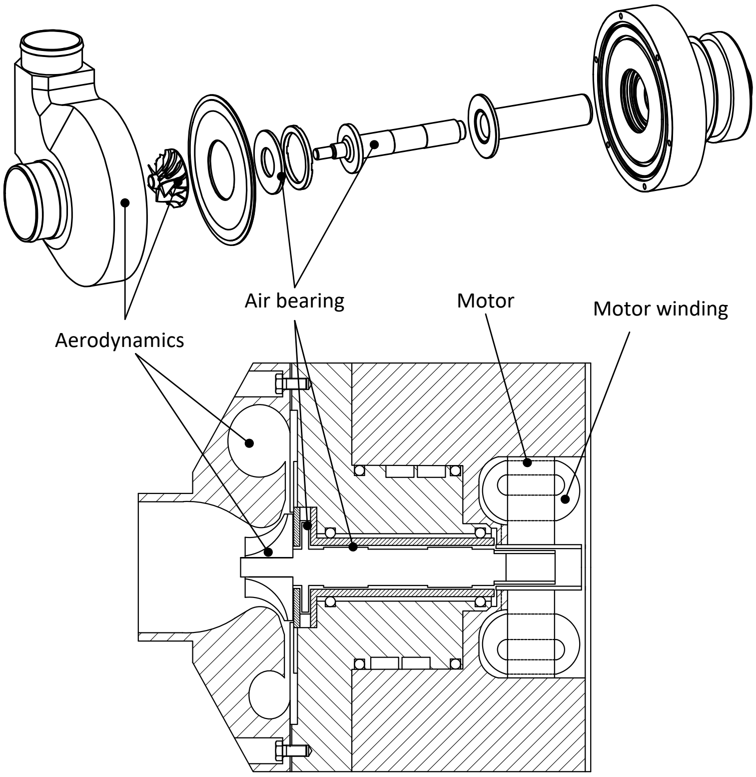


Figure 3: Compressor building blocks: motor, motor winding, aerodynamics, air bearing.

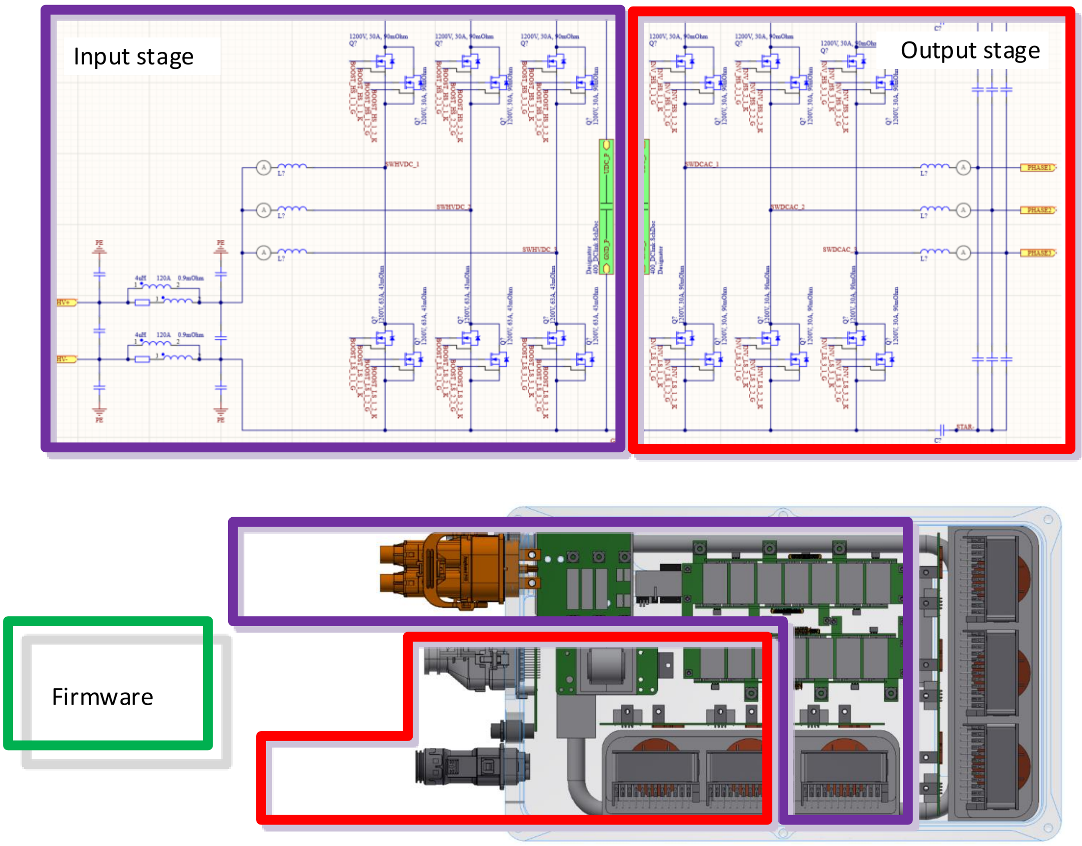


Figure 4: Converter building blocks: converter input stage, converter output stage, and firmware.

With the results and findings of this project, compressor systems with lower cost and lower validation effort than fully application specific compressor systems, and higher efficiency than usage of existing non-optimal compressor systems, shall become feasible, while still remain flexible for the current fuel cell market situation with non-standardized specifications. In this project, the applicable standardization and the remaining flexibility shall be investigated (results see section 3.1).

2 Procedures and methodology

2.1 Project plan and works packages

To be able to achieve the abovementioned objectives, the work packages according to the project plan in Figure 5 are executed.

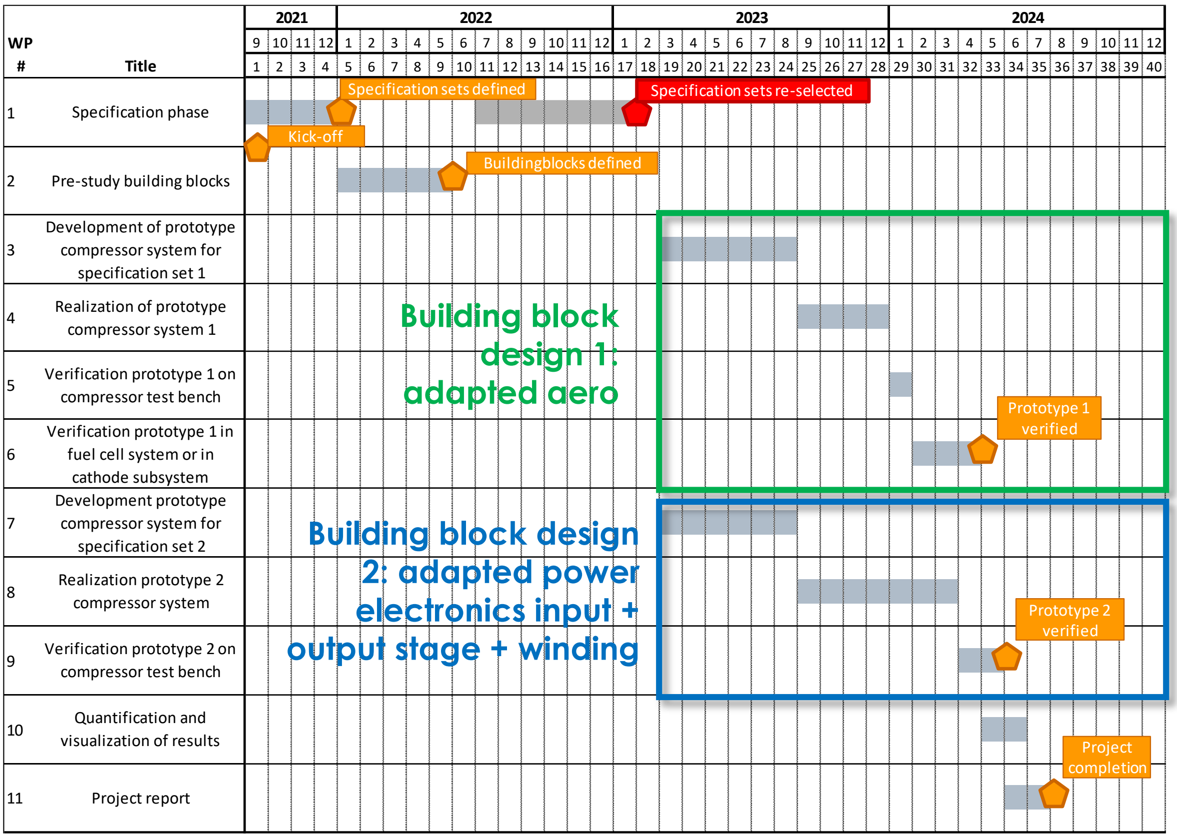


Figure 5: Project plan.

2.2 Methodology and roles of partners

The methodology for WP 1 is to interview customers (including OPmobility), experts and other market players to collect specifications. Subsequently, the specifications are categorized into specification sets. This is undertaken by Celeroton, OPmobility is one of the customers interviewed.

The methodology for WP 2 is to implement models to calculate the KPIs according to Table 2. Celeroton implements all models except the model for fuel cell efficiency is based on a model of OPmobility.

The methodology for WP 3 to 5 and 7 to 9 is based on the development process of Celeroton as depicted in Figure 6, undertaken by Celeroton.

The methodology for WP 6 is testing at OPmobility according to internal OPmobility standards.

The methodology for WP 6 is testing at OPmobility according to internal OPmobility standards. Celeroton's role is to support OPmobility.

WP 10 and 11 are executed by Celeroton as desktop work, with inputs provided by OPmobility for quantification of the results.

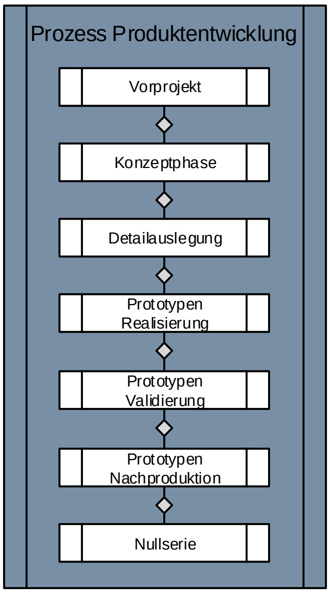


Figure 6: Development process for WP 3-5 and 7-9.

3 Results and discussion

3.1 Specifications

Specification sets investigated in this activity are from these sources:

- Existing compressor systems of Celeroton
  - These specification sets are based on the specifications for the existing compressor systems of Celeroton in the fuel cell power range of 45 – 60 kW, which resulted out of different past customer inquiries
- Inquiries of customers of Celeroton
  - These specification sets are based on inquiries of potential customers at Celeroton in the fuel cell power range of 20 – 60 kW that cannot be covered with existing compressor systems yet.
- Inquiries of market players
  - Extended market research including inquiries from market players who have not been contacted thus far is conducted.
- Existing fuel cell projects at OPmobility
  - These specification sets are based on existing projects at OPmobility in the fuel cell power range of 20 – 60 kW.

Specifications in the fuel cell industry are and will stay dynamic, standardization is being established, but slower than expected and forecasted. This also affects this project with change in specifications during the project and therefore a delay in the according work package. Nonetheless, the applications and market players according to Figure 7 are identified, and for each application, the specifications are elaborated based on customer interviews, online information and/or market reports. All applications with requirements or specifications that cannot be covered within the project due to the technical limitations of the baseline system are eliminated. Finally, the resulting specifications are compiled into four categories that cover as many applications as possible. An overview of the results is shown in Figure 8.

Besides the specifications identified in this project based on market studies and customer interviews in this project, the standardization and remaining flexibility required can be framed with the following vectors:

- Technical: mass flow and PR
    - No standardization in pressure ratio and mass flow requirements is present for the different fuel cell power classes. The fuel cell system integrators and stack manufacturers either a) use standard compressors and accept the disadvantages in efficiency and operating range or the compressor, or b) invest into a custom design, or c) now according to this project choose a building block design (with smaller efficiency and operating point range disadvantages than a), or d) invest (with much smaller duration and cost than b) into a new building block design.
- Technical: input voltage range
    - Standardization is happening at fuel cell system integrators in the high-voltage range with HV2 (~400 Vdc) and HV3 (~800 Vdc) voltage levels
    - No standardization is established thus far in low voltage requirements between 36 and 80 Vdc
- Quantities and diversification
    - Current quantities for compressors are a few 10 to a few 100 per fuel cell application. Per compressor power class 2 to 4 building block designs are applicable (usually with 1 customer per building block design).
- Cost sensitivity
    - The market requires for prices with lowest initial costs, i.e. no initial cost for customized development (of fully custom or building block design) is foreseen in the fuel cell project.
- Time to market:
    - The market requires for lead times between 2 to 12 months depending on the fuel cell project.

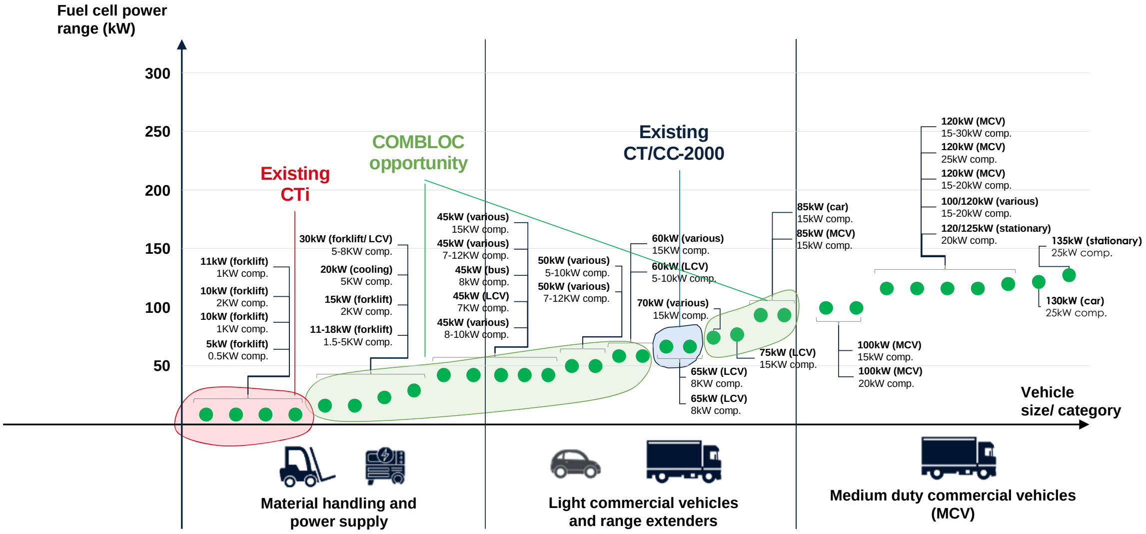
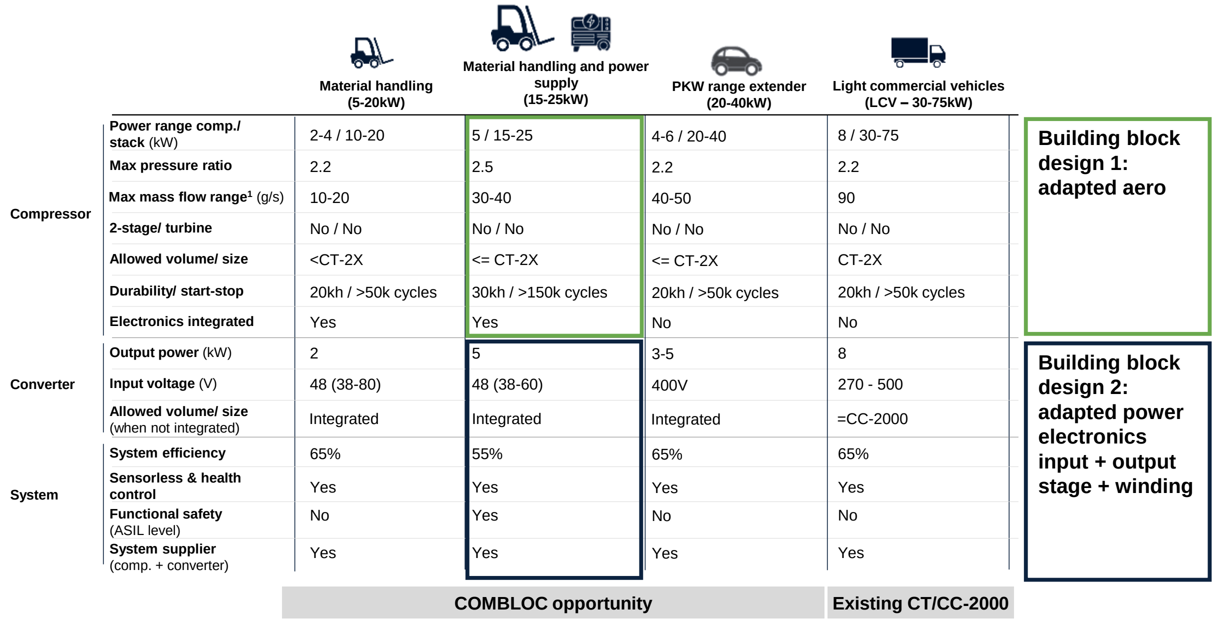


Figure 7: Applications identified in extended market evaluation for which specifications are elaborated.



		Material handling (5-20kW)	Material handling and power supply (15-25kW)	PKW range extender (20-40kW)	Light commercial vehicles (LCV – 30-75kW)	
Compressor	**Power range comp./ stack** (kW)	2-4 / 10-20	5 / 15-25	4-6 / 20-40	8 / 30-75	**Building block design 1: adapted aero**
	Max pressure ratio	2.2	2.5	2.2	2.2	
	Max mass flow range[1] (g/s)	10-20	30-40	40-50	90	
	2-stage/ turbine	No / No	No / No	No / No	No / No	
	Allowed volume/ size	<CT-2X	<= CT-2X	<= CT-2X	CT-2X	
	Durability/ start-stop	20kh / >50k cycles	30kh / >150k cycles	20kh / >50k cycles	20kh / >50k cycles	
	Electronics integrated	Yes	Yes	No	No	
Converter	**Output power** (kW)	2	5	3-5	8	**Building block design 2: adapted power electronics input + output stage + winding**
	Input voltage (V)	48 (38-80)	48 (38-60)	400V	270 - 500	
	Allowed volume/ size (when not integrated)	Integrated	Integrated	Integrated	=CC-2000	
System	**System efficiency**	65%	55%	65%	65%	
	Sensorless & health control	Yes	Yes	Yes	Yes	
	Functional safety (ASIL level)	No	Yes	No	No	
	System supplier (comp. + converter)	Yes	Yes	Yes	Yes	
		COMBLOC opportunity			**Existing CT/CC-2000**	

Figure 8: Specification sets complied into four categories and selected specification sets for this project.

The material handling market is identified as a growth market with high-potential, based on the prominence of customer inquiries from this field. Furthermore, feedback obtained in the customer interviews confirmed that the material handling market is not only growing in the number of systems installed in the field, but also the power rating of the fuel cell systems realized by Celeroton's customers is ever-extending to cover additional segments of the market. As an additional advantage, the market for power supply units requires similar aerodynamic and electrical specifications. Therefore, it could be covered by the same aerodynamic designs, making such a solution particularly attractive as it would enable extended coverage of two additional market segments for Celeroton.

The necessary aerodynamic operating points can be covered with an adaptation of the baseline compressor design towards a lower nominal mass flow and higher pressure ratio. For the power electronic converter, the nominal voltage needs to be adapted to the standardized ratings of the backup batteries that are currently used for these applications. Three different nominal ratings are most widely spread: 24 V, 48 V, and 80 V. The 48 V nominal rating provides a good trade-off between the complexity reduction due to the lower system voltage (required insulation, safety precautions) and the increased input current needed to sustain the power demand of the turbo compressor. Therefore, the 48 V class is attractive for the building block converter design.

Therefore, the two specification sets selected to be evaluated with a building block compressor design and validation within this project are:

- The first specification has an adapted aerodynamic design required for material handling or power supply applications (building block compressor design 1).
- The second specification set has an adapted nominal voltage of 48 V required for material handling or power supply applications (building block compressor design 2).

3.2 Building blocks study

3.2.1 Required building blocks

For specification set 1, the adaption of the following building blocks is required:

- the aerodynamic components

For specification set 2, the adaption of the following building blocks is required:

- the converter input and output stage
- the motor winding

The other building blocks can be kept for both specification sets:

- the converter firmware
- the gas bearing
- the electric machine (beside the winding)

3.2.2 KPI models

The KPI model implementation and model testing results in the model accuracies according to*Table 3*.

KPI	Target values / limits for BB compressor vs. custom specific design	Modelling / Verification	Implemented model: accurate, average, limited accuracy
Size/weight	+50%	Size/weight scaling models based on existing compressors and converters (size and weight scale proportionally for the same compressor technology)	Size/weight scaling models based on existing compressors and converters (size and weight scale proportionally for the same compressor technology)
Product cost	+10%	Cost models based on existing compressors	Cost models based on existing compressors
Compressor efficiency	-5%	Aerodynamic preliminary designs + efficiency models based on existing compressors and converters	Aerodynamic preliminary designs + efficiency models based on existing compressors and converters
Fuel cell efficiency / primary energy consumption	-1% / +1%	Simplified fuel cell models	SH FC model
Net power output (fuel cell power minus compressor power)			SH FC model
Design effort		New model to be defined in project	CEL Bottom-up cost calculation
Design effort	-50%	New model to be defined in project	CEL Bottom-up cost calculation

Table 3: KPIs according to implementation.

A matrix is built up to identify the necessary building blocks to meet particular specification sets, and to summarize the KPI results. For the comparison of the compressor systems based on building blocks to a custom designed compressor system, models of the KPIs according to Table 2 are implemented, as an example the KPI model for converter size vs. converter power and input voltage for a custom designed compressor is depicted in Figure 9.

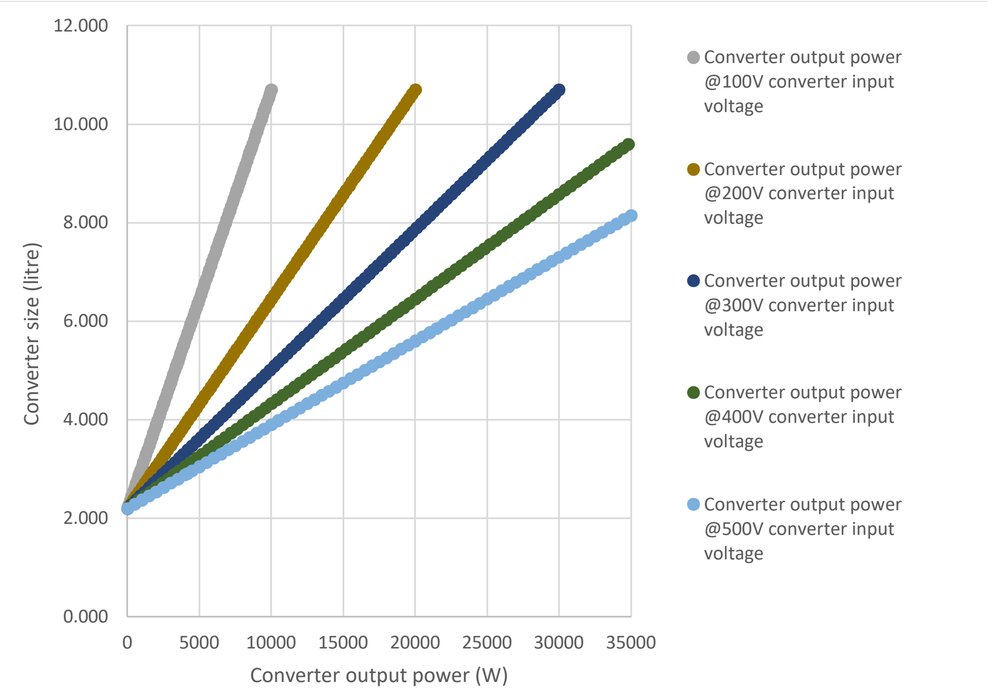


Figure 9: KPI model for converter size vs. converter output power and input voltage for a custom designed compressor system.

3.2.3 Results (building block / specification set matrices)

As described above, for the selected specification sets as of Figure 8 the consolidated building block / specification set matrices are depicted for building block model 1 / specification set 1 (Table 4) and the combination of building block model 1+2 / specification set 1+ 2, as building block model 2 only makes sense in combination with building block model 1 (Table 5).

The results for building block design 1 / specification set 1 (Table 4) are:

- The size of the building-block compressor system is around 10% bigger, which is expected
- There is almost no impact on the product cost
- The reduction in efficiency is close to the maximal limits as of Table 2
- There is a major reduction in design and validation effort, which is expected

The results for combining building block design 1 and 2 / specification set 1 + 2 (Table 5) are:

- The size of the building-block compressor system is around 16% bigger, which is expected
- There is no impact on the product cost
- The reduction in efficiency is due to building block model 1, there is not additional efficiency decrease as the converter for the building block model 2 as also for a custom design is new.

- There is a major reduction in design and validation effort, however not as big as for bulding block model 1 only due to the new converter and motor winding

	Comparison	BB System	Custom
Size (lt)	9%	8.32	7.66
Weight (kg)	2%	10.90	10.68
Product cost @ 1000 pieces	-2%		
Compressor system efficiency (P_is/P_dc_in)	-4.7%	57.7%	62.4%
Fuel cell stack efficiency	0%	49.6%	49.6%
Fuel cell system efficiency	-0.5%	43.0%	43.5%
Net output power (kW)	-1.2%	25.7	26.0
Design effort	-91%		
Validation effort	-73%		
Adapted building blocks	Aero	Aero	All new

Table 4: Building block / specification set matrix for specification set 1.

	Comparison	BB System	Custom
Size (lt)	16%	14	12
Weight (kg)	16%	24	21
Product cost @ 1000 pieces	0%		
Compressor system efficiency (P_is/P_dc_in)	-4.7%	57.7%	62.4%
Fuel cell stack efficiency	0%	49.6%	49.6%
Fuel cell system efficiency	-0.5%	43.0%	43.5%
Net output power (kW)	-1.1%	25.6	25.9
Design effort	-70%		
Validation effort	-46%		
Adapted building blocks	Power electronics input + output stage + motor winding	Power electronics input + output stage + motor winding	All new

Table 5: Building block / specification set matrix for specification set 1 + 2 combined.

3.3 Building block designs

The two building blocks target for two different requirements:

- Building block compressor design 1: allows to cover a variety of fuel cell stacks and systems developed for material handling and power supply applications, requiring higher pressure ratio and lower mass flow than the baseline system CT-2000).
- Building block compressor design 2: allows to cover fuel cell applications that employ a low voltage battery, such as often used in material handling.

The two building blocks can be applied individually or combined (i.e. for a fuel cell system requiring higher pressure ratio and lower mass flow than the baseline system plus providing low input voltage), i.e. they allow for a modular approach.

3.4 Building block compressor design 1 (“adapted aero”)

To cover the specification set 1, the aerodynamics have to be adapted to lower mass flow and higher pressure ratio as depicted in Figure 10, resulting in an aerodynamic design with larger diameter and shorter wings. In total, this leads to a smaller shaft power required. The rotational speed for an optimal aerodynamic design would be higher, but is limited by the baseline system with a resulting efficiency decrease compared to a custom design compressor where the rotational speed can be selected.

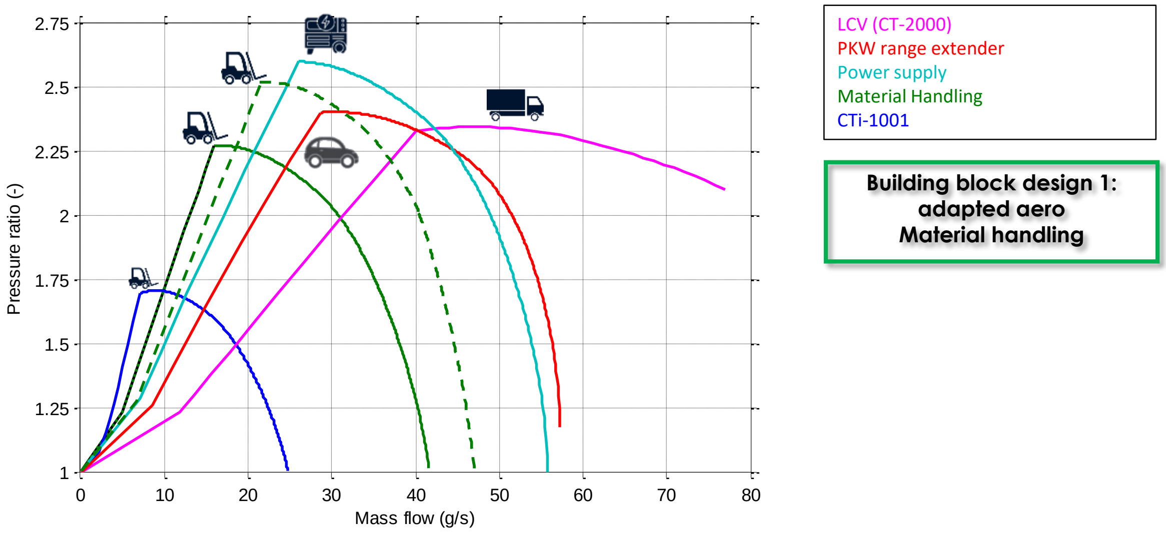
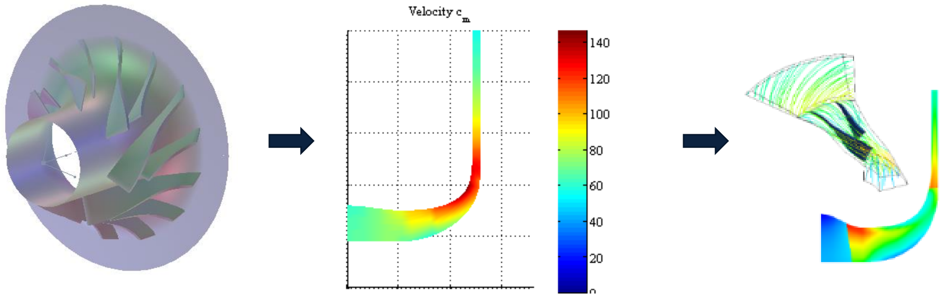


Figure 10: Building block design 1: Adapting the aerodynamics from the baseline system LCV (CT-2000) to the material handling pressure ratio and mass flow requirements.

3.4.1 Aerodynamic design

The compressor aerodynamics components (impeller, diffusor and volute) are adapted to the defined target operating range, taking into account the maximum rotational speed of the base system design and the maximum power capability of the electronics. The necessary performance is achieved with a small increase of the impeller diameter and a re-design of the blade and volute geometries. The aerodynamic design flow is depicted in Figure 11. The calculated compressor and power maps are shown in Figure 12 - Figure 13.

The building block aerodynamic design leads to a lower efficiency than a custom aerodynamic design, as the rotational speed for the building block design is fixed and non-optimal concerning aerodynamic efficiency. The calculated isentropic aerodynamic efficiency for the building block aerodynamic design is 66.6% at the design point and for standard inlet conditions (T_{in} = 20°C and p_{in} = 1 bara), vs. an efficiency of 71.5% for a custom aerodynamic design at optimum rotational speed. This leads to a total compressor system efficiency of 62% (custom compressor system design) and 57% (building block compressor system design) respectively.



2D Design

2D Calculations / Optimization

3D CFD Analysis

Figure 11: Aerodynamic design flow.

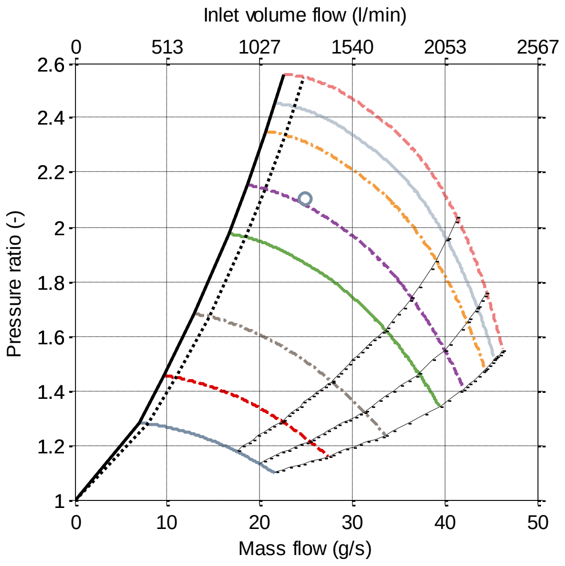


Figure 12: Calculated aerodynamic compressor map at standard inlet conditions (T_{in} = 25°C and p_{in} = 1 bara).

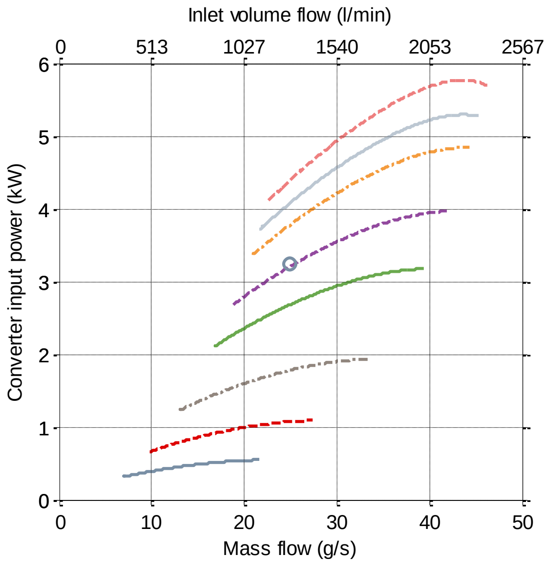


Figure 13: Calculated converter input power map at standard inlet conditions (T_{in} = 25°C and p_{in} = 1 bara).

3.4.2 Thrust bearing and rotor dynamics feasibility

The increased pressure ratio of the adapted aerodynamics increases the axial thrust acting on the rotor. Hence, the feasibility of the gas bearing needs to be confirmed before the realization. Furthermore, the adapted impeller design has an increased outer diameter and a higher weight. Therefore, the rotor dynamics need to be recalculated to confirm stability operation across the target operating range.

The calculated safe operating area of the gas bearings is shown in Figure 14 for nominal operating conditions. The results confirm that no adaptation of the gas bearing is needed, because the existing design can sustain the increased axial thrust.

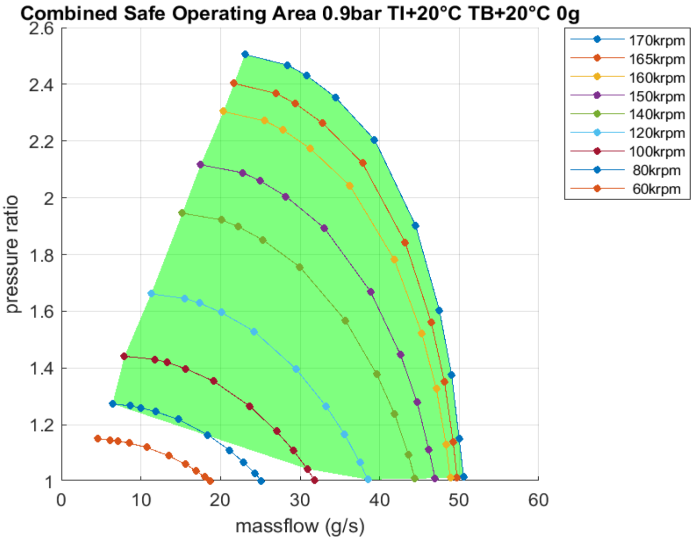


Figure 14: Safe operation area at 0.9 bara inlet pressure.

Rotor dynamics calculations for the increased impeller diameter and weight show that the first bending mode of the rotor base design is not drastically changed and no critical change to the mechanical stability is expected. Hence, the rotor design does not need to be modified in order to realize the adapted aerodynamics.

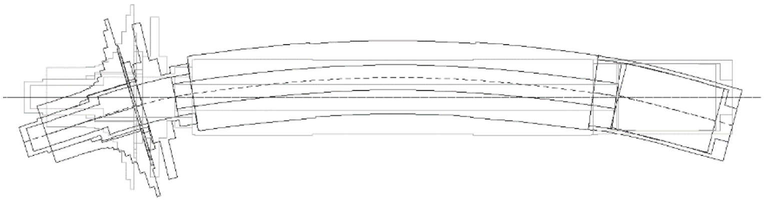


Figure 15: First bending mode of the rotor.

3.4.3 Thermal feasibility

The higher compression ratio and the gas bearing losses at the adapted operating conditions require a re-evaluation of the thermal design of the compressor. A thermal finite-element method (FEM) simulation of the compressor is undertaken for nominal operating conditions and a cooling with a coolant flow rate of 6 l/min and at 65°C coolant temperature. The simulation results confirm that all components are operated within their temperature ratings and show that the thermal feasibility of the compressor design is given.

3.4.4 Validation

The validation is undertaken first at Celeroton on an aerodynamic test bench, as depicted in Figure 16, generating the measurement results as of Figure 17 and Figure 18. Subsequently the compressor is validated at OPmobility on a fuel cell test bench, as depicted in Figure 21. The measured efficiency by OPmobility in the specification set 1 operating point is 54.2% (compared to the design value of 57.7%). The mass flow measured at OPmobility is lower and the power consumption larger than in the measurements at Celeroton. The reason is assumed to be a flow detachment in a partial area of the pipe due to the 90° bend at the inlet of the compressor in the test setup at OPmobility, potentially combined with a measurement inaccuracy in one or both mass flow measurements.

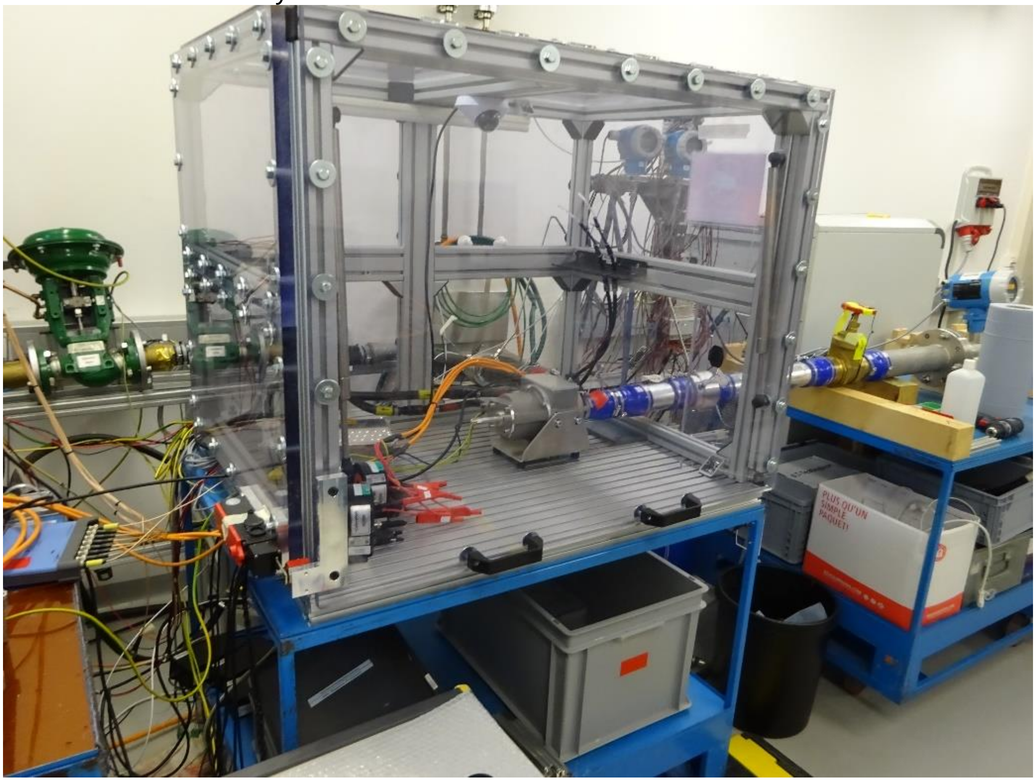


Figure 16: Validation on Celeroton aerodynamic test bench.

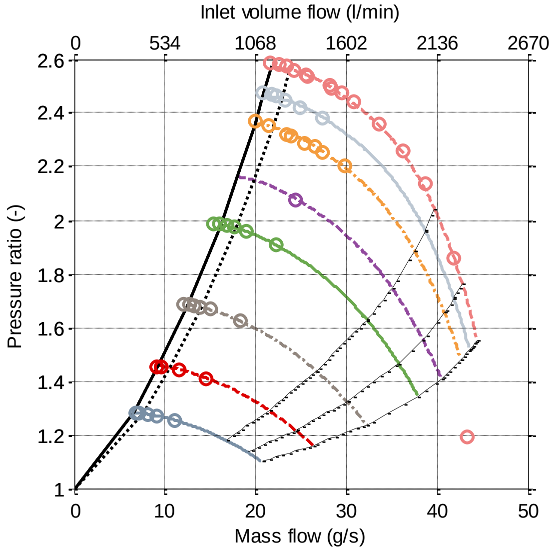


Figure 17: Measured aerodynamic compressor map at laboratory inlet conditions (T_{in} = 23°C and p_{in} = 0.955 bara).

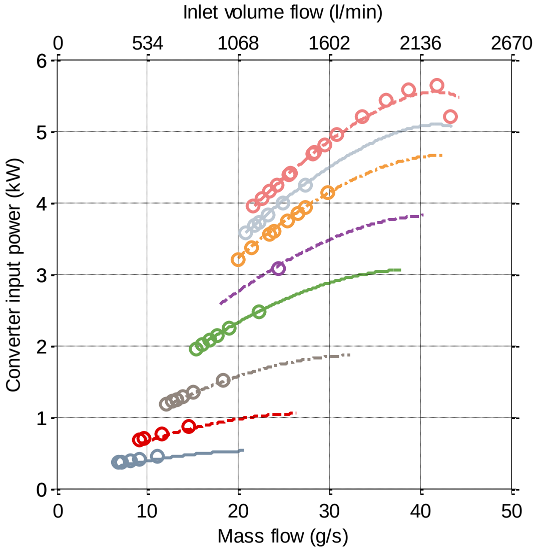


Figure 18: Measured converter input power map at laboratory inlet conditions (T_{in} = 23°C and p_{in} = 0.955 bara).

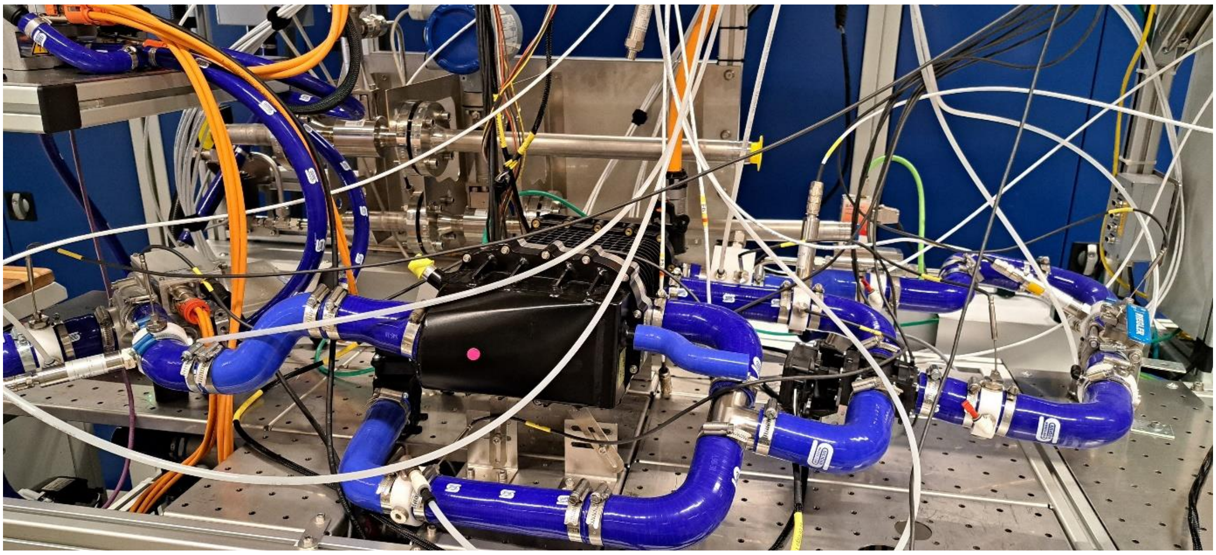


Figure 19: Validation on OPmobility fuel cell test bench – overall test bench setup.

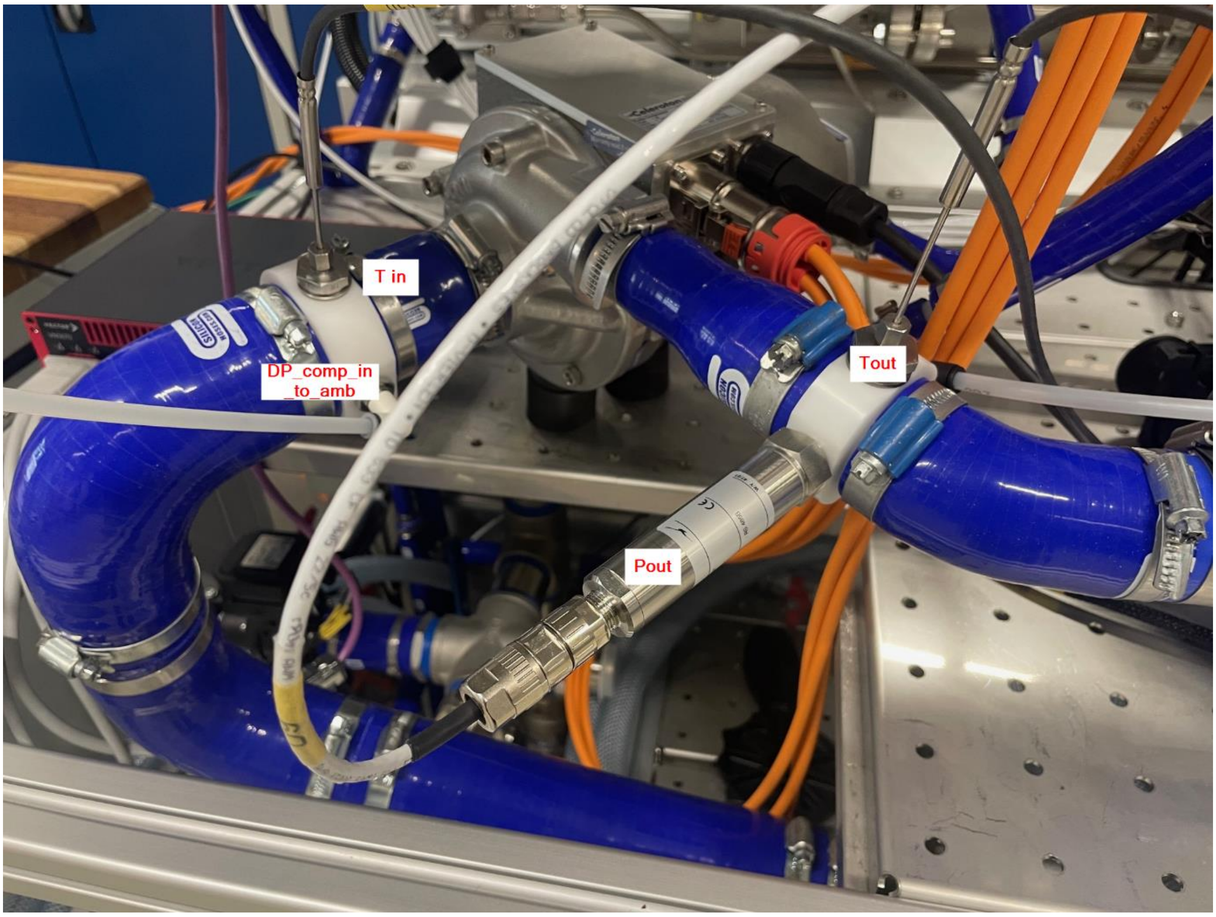


Figure 20: Validation on OPmobility fuel cell test bench – building block compressor 1 prototype installation and sensor positions.

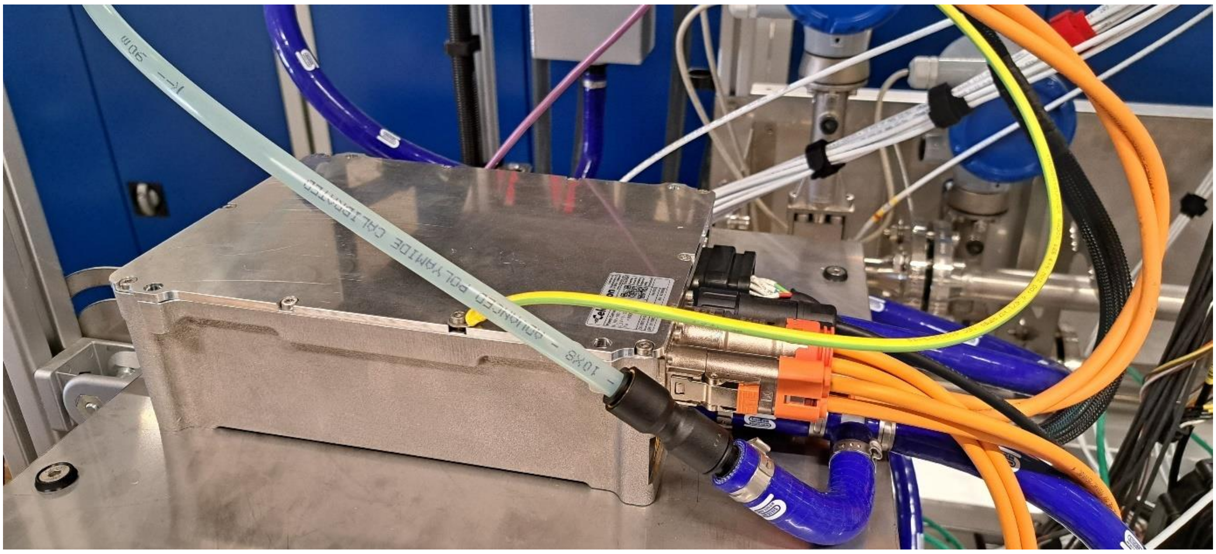


Figure 21: Validation on OPmobility fuel cell test bench – converter installation.

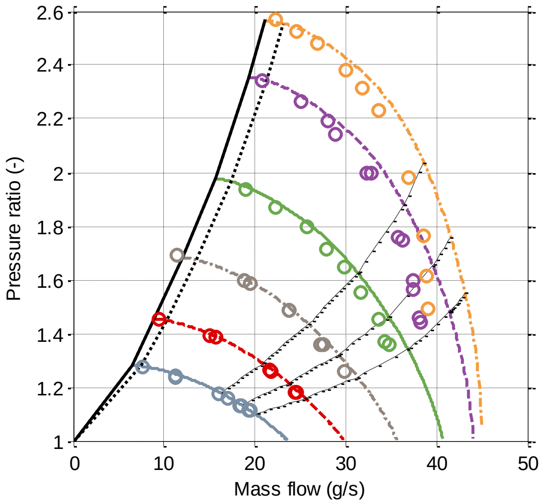


Figure 22: Measured aerodynamic compressor map at fuel cell test bench inlet conditions (T_{in} = 24°C and p_{in} = 0.93 bara).

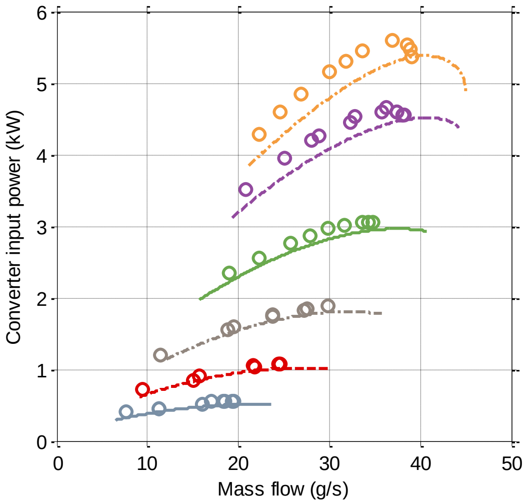


Figure 23: Measured converter input power map at fuel cell test bench inlet conditions (T_{in} = 24°C and p_{in} = 0.93 bara).

3.5 Building block compressor design 2 (adapted power electronics input + output stage + winding)

Specification set 2 asks for lower input voltage, while the compressor and therefore motor power stays the same, resulting in a higher input current. Many material handling applications demand that the compressor system has to work from such low input voltages due to the choice of the battery.

3.5.1 Adaption of the motor winding and power electronics

To account for the reduction of the input voltage to 48 V nominal voltage, and adaptation of the motor winding configuration and the power electronics topology is required. To achieve an optimized over-all solution, the motor and the power electronics must to be considered as a single mechatronic system and jointly optimized taking all factors into account.

The stator construction of the base product consists of four coils per motor phase as shown in Figure 24. The can be connected in series or in parallel to adjust the motor back EMF. The target value for the back EMF is strongly linked to the selected power electronics topology. The following options were considered:

- Motor winding configurations with Y-connection, delta-connection or with star point.
- Power electronics inverter topology for Y- or delta-connection of the motor phases or for open star point configuration.
- Power electronics topology for direct operation from the input voltage (48 V nom., full power operating range 38 – 60 V).

- Power electronics topology with integrated DC-DC boost converter front-end in the power electronics in order to stabilize the DC-link to a constant 60 V.

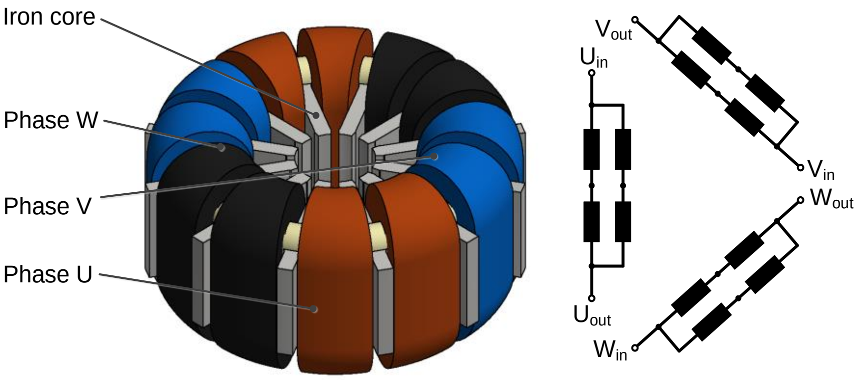


Figure 24: Stator with interconnections of the phase coils adapted for 60V operation.

A detailed evaluation of different motor configurations and power electronics topologies was conducted based on the following evaluation criteria:

- Motor
    - Phase current
    - Manufacturability
- Electronics
    - Current stress of the converter
    - Construction volume
    - Efficiency
- System cost

Based on the detailed evaluation of different concepts, the solution for the motor winding configuration as shown in Figure 24 and power electronics topology incorporating a DC-DC boost converter front-end to stabilize the DC-link to a constant 60 V is selected. This enables a significant reduction of the required phase currents and thereby drastically increases the electrical efficiency of the motor. Furthermore, the design of the power electronics is simplified due to the lower current, which also enables a cost reduction.

3.5.2 Semiconductor design, losses and efficiency

A considerate choice of the power semiconductor technology is required to maximize the electrical efficiency of the power electronics. Furthermore, a miniaturization of the power electronics converter is necessary in order to account for the limited available space in typical customer applications. Hence, the main driving factors for the choice of the power semiconductors are the energy efficiency and the attainable switching frequency, which finally defines the design volume of the power electronics.

The following design options were considered:

- Low-voltage silicon (Si) MOSFET technology
- Low-voltage gallium nitride (GaN) HEMT technology
- High-voltage silicon carbide (SiC) MOSFET technology

For each option, the maximum achievable switching frequency, the power losses and the impact on the total system cost were evaluated. Based on this evaluation, the GaN power semiconductors were identified as the preferred semiconductor technology. According to the power loss measurements shown Figure 25, a switching frequency up to 400 kHz can be achieved for 60 V DC-link voltage and a phase current of up to 50 A rms.

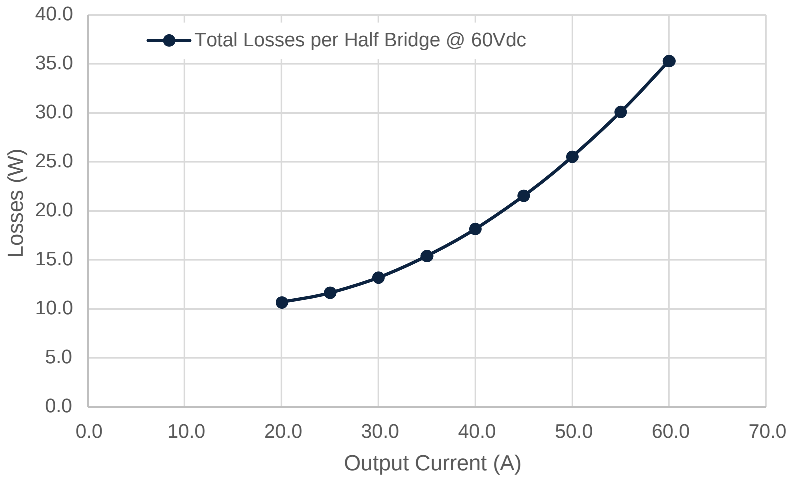


Figure 25: Measured total power semiconductor losses for EPC2302 GaN devices (per half-bridge, 400 kHz, 60 V DC).

The building block aerodynamic design leads to the same efficiency as a custom design, as the converter is a full new design in both cases, and the compressor remains the same, respectively the change in motor winding does not influence the efficiency.

3.5.3 Electronics housing and thermal design

The selected power semiconductor devices are surface mounted devices (SMD), which are soldered to a power PCB and require contact cooling via the casing top-side. Therefore, the electronics housing was designed with an integrated heatsink as shown in Figure 26. For the thermal interface between the SMD devices and the heatsink, a heat distribution plate is attached directly to the power PCB. The PCB with the assembled heat distribution plate is then pressed to the top-side of the heatsink in order to minimize the thermal resistance to the liquid cooling.

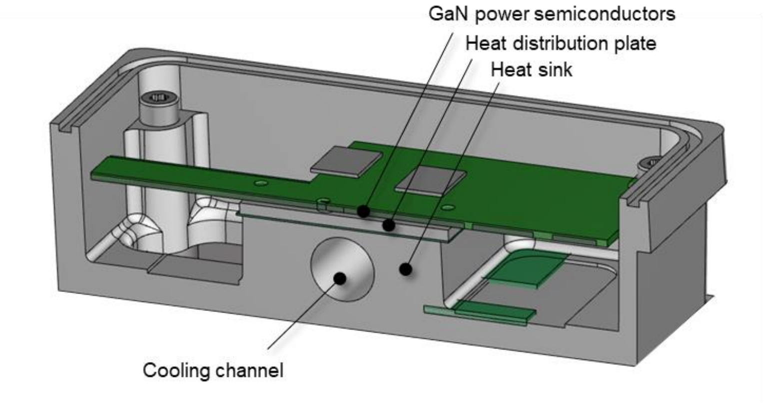


Figure 26: Power electronics cooling concept (top: cooling concept for the GaN power semiconductors; bottom: cross-section of converter housing with integrated cooling channel).

In order to verify the design calculations for the cooling of the power semiconductors and the inductors of the EMI filter and the output filter, a thermal simulation is performed for a simplified model of the converter housing with the integrated heatsink. The results for the calculated local temperature distribution inside the housing confirm that all components are operated within their specifications.

3.5.4 Realization of laboratory prototype

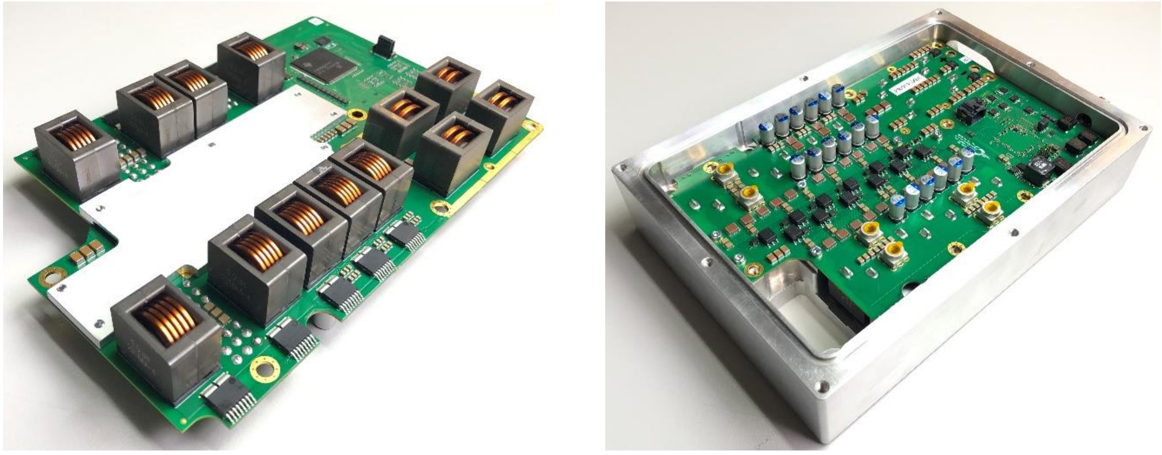


Figure 27: Photographs of the prototype power converter (left: bottom side of power PCB with heat distribution plate; right: top side of power PCB mounted into prototype housing).

Based on the described design calculations, a prototype converter is realized for the experimental verification. The prototype power PCB with the assembled heat distribution plate and the assembled converter including the housing are shown in Figure 27. The converter was successfully taken into operation and first tests confirm that the validation can be started as planned.

Based on the design adaptions as of chapter 3.5.1, a prototype stator with adapted winding is realized.

3.5.5 Validation

The stator is validated with comparing measured and designed phase inductance and resistance according to Table 6.

	Design	Measurement	Unit
Phase a resistance	9.14	9.49	mΩ
Phase b resistance	9.14	9.55	mΩ
Phase c resistance	9.14	9.75	mΩ
Phase a inductance	22.3	28.1	µH
Phase b inductance	22.3	27.9	µH
Phase c inductance	22.3	37.1	µH

Table 6: Validation of prototype stator with adapted winding.

Figure 28: Validation of basic functionality in electronics laboratory at Celeroton.

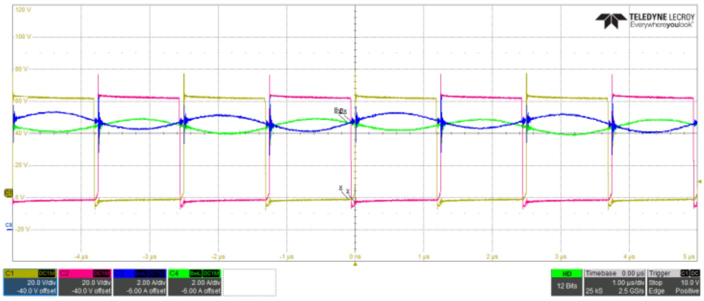


Figure 29: Measured GaN power semiconductor switching transitions
(60 V DC, phase current 14 A DC, PWM frequency 400 kHz, 50% duty cycle).

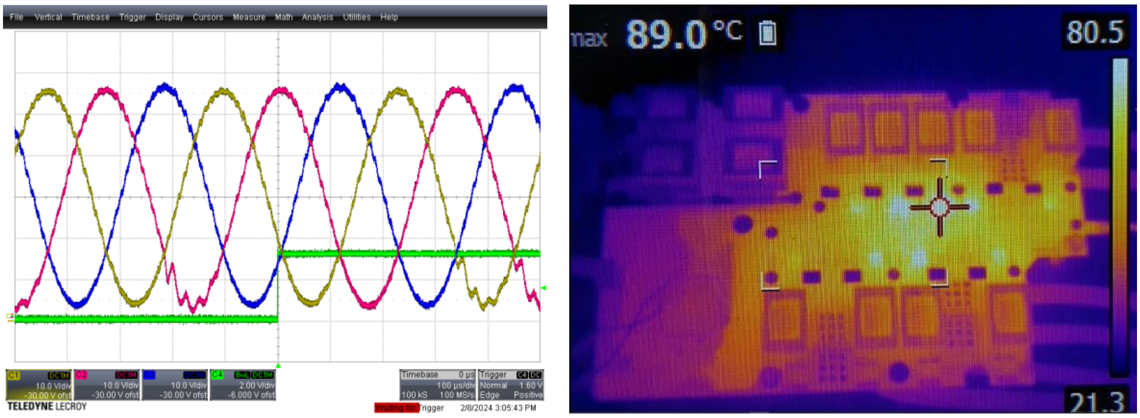


Figure 30: Verification of the motor current modulation (left) and thermal validation of the prototype power converter (right) (motor speed 180 krpm, input voltage 60 V DC, PWM frequency 400 kHz).

4 Quantification of results and conclusions

This project results in the following conclusions and results for the broader use by the fuel cell and more specifically system integrator community:

- A comparison to other state-of-the-art compressors in the field of 15-40 kW fuel cell stack compressors, according to Table 7 shows:
  - The size and weight savings with a custom design compared to a building block design are below 10%.
  - Also, a building block design is around a factor of 2 to 2.5 smaller in size compared to the state-of-the-art.
  - Also, a building block design has outperformed the state-of-the-art in terms of efficiency by 1.6 up to 10.2% (and probably more, as measured efficiencies are usually significantly lower than datasheed values).
  - With a custom design another significant improvement of 4.7% in efficiency is possible.

	Custom design	Building block 1 des.	Competitor 1	Competitor 2	Competitor 3	Unit
Size	7.66	8.32	16.75	20.08	19.82	lt
Weight	10.68	10.90	10	14.4	13.5	kg
Efficiency at specification set 1 design point	62.4 (design)	54.2 (measured) 57.7% (design)	52.6 (datasheet)	48.9 (datasheet)	44.0 (datasheet)	%

Table 7: Comparison to other air compressor systems for 15-40 kW fuel cell stack power.

- Specifications in the fuel cell industry are and will stay dynamic, especially in pressure/flow requirements, whereas more standardization is already present in ambient conditions and power classes. For the voltage levels, a standardization is happening at fuel cell system integrators in the high-voltage range (with HV2 and HV3 voltage levels), but standardization is present at low voltage requirements between 36 and 80 Vdc.

- The maximum range of fuel cell power classes that can be covered with only modifying building blocks in a baseline compressor, and limiting the compressor efficiency reduction to 5%, is around 40-100%, i.e. with the investigated baseline compressor as of this project a range in fuel cell power class from 25 to 60 kW (or e.g. a baseline compressor for the next size fuel cell power class can cover a range of 60-150 kW fuel cell systems. This allows to reduce the design and validation effort compared to a custom design up to 90%.
- The input voltage can be adapted without impact on the efficiency, however it requires significant design adaptions and validation, but still reduces the design and validation effort compared to a custom design up to 46%.
- A building block design has minimal impact onto the piece price in serial production, therefore, for single applications with large quantities custom designs will remain.

5 Outlook and next steps

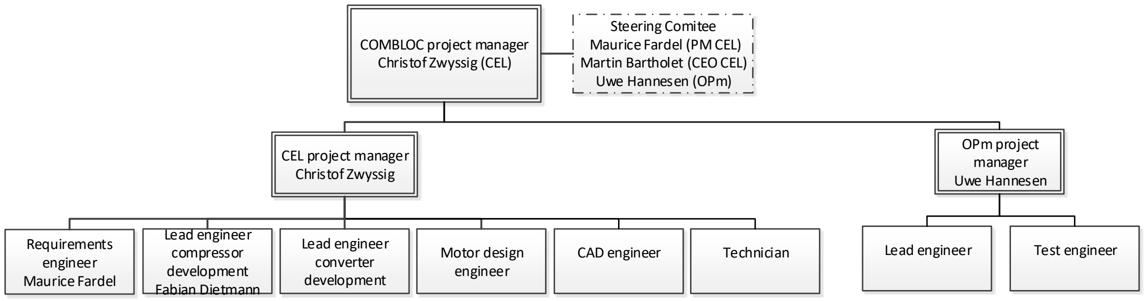
Subsequent to the project the project results are shared with customers and partner of Celeroton in order for Celeroton, SH and customers and partner to take decisions about specifications for future fuel cell systems. Furthermore, the results are integrated into the product portfolio strategy at Celeroton. Finally, the building block systems designed in this project will be further developed into products of Celeroton and made accessible to the fuel cell market.

6 National and international cooperation

The project consortium is built from two organization:

- Main partner: Celeroton (CEL)
- Member of consortium: OPmobility (OPm)

The project is organized according to the following structure:



In addition, Celeroton and OPmobility collaborate with national and international suppliers, customers and other partner in the hydrogen and fuel cell community and market.