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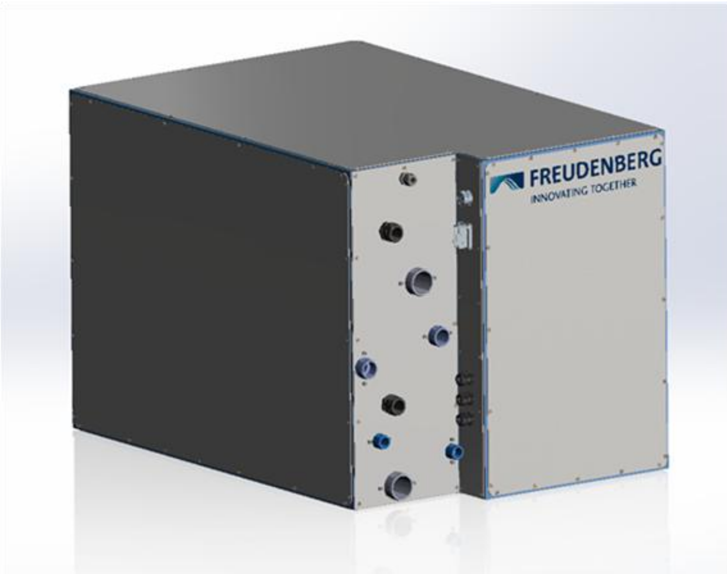
Final Design of Freudenberg FCM



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1 Introduction

Freudenberg e-Power Systems is a leading provider of electrical power solutions for the global heavy-duty markets. Based on long-term experience in fuel cell technologies, Freudenberg combines component knowledge with a holistic system understanding. To serve heavy-duty applications, our fuel cell systems are designed for best-in-class total cost of ownership. The unique design aims to meet the needs of heavy-duty customers and end-users: a long and low-maintenance lifetime combined with consistently high overall efficiency.

2 WP3 standard overview

The following sub-sections provide an overview of the WP3 standard definition, which is necessary to verify the compliance of the FCM design according to the StasHH definitions. The exact and binding requirements are listed in the official documents. A minimum power output of 30 kW (Beginning of life, BOL) of the FCM is mandatory for the StasHH standard.

2.1 Standard size definition

Three series of FC boxes were defined within the standard: A, B, and C series. For the A-series a doubling in the height direction is possible, which will be denoted with the subscript AA. The B-series allows for doubling or tripling in height direction denoted with the subscript BB and BBB, respectively. The dimensions of the boxes can be found in Table 1 and the following tolerances in all directions are tolerated: +0/-100 mm.

Table 1: dimensions FC module A, B and C

StasHH	Length / mm	Width / mm	Height / mm	Expected PEM kW
A	1.020	700	340	50
AA	1.020	700	680	110
AAA	1.020	700	1020	160
B	1.360	700	340	70
BB	1.360	700	680	145
BBB	1.360	700	1.020	220
C	1.700	700	340	90

The respective volumes of the assorted sizes are as follows:

- A external volume is max. 0.243 m^3
  AA external volume is max. 0.486 m^3
  AAA external volume is max. 0.729 m^3
- B external volume is max. 0.324 m^3
  BB external volume is max. 0.647 m^3
  BBB external volume is max. 0.971 m^3
- C external volume is max. 0.405 m^3

A visual representation of the A to C series boxes including the multiple sizes is shown in Figure 1.

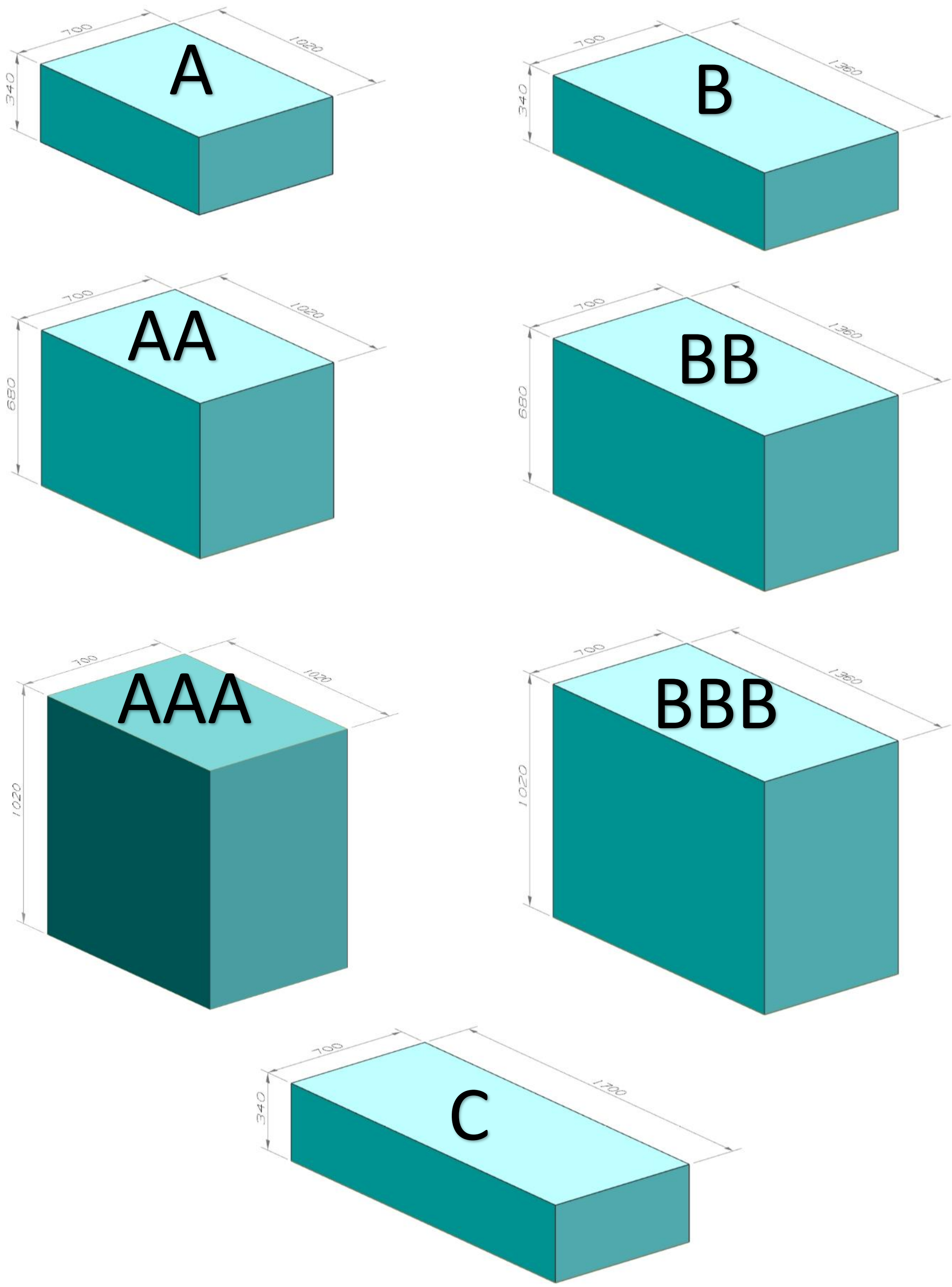


Figure 1: FC modules A, B and C

The orientation of all FC boxes is fixed according to the LengthxWidthxHeight definition except for the A(A) boxes which can be orientated optionally on its side. This is not a StasHH requirement. The optional orientation on the side is shown in Figure 2

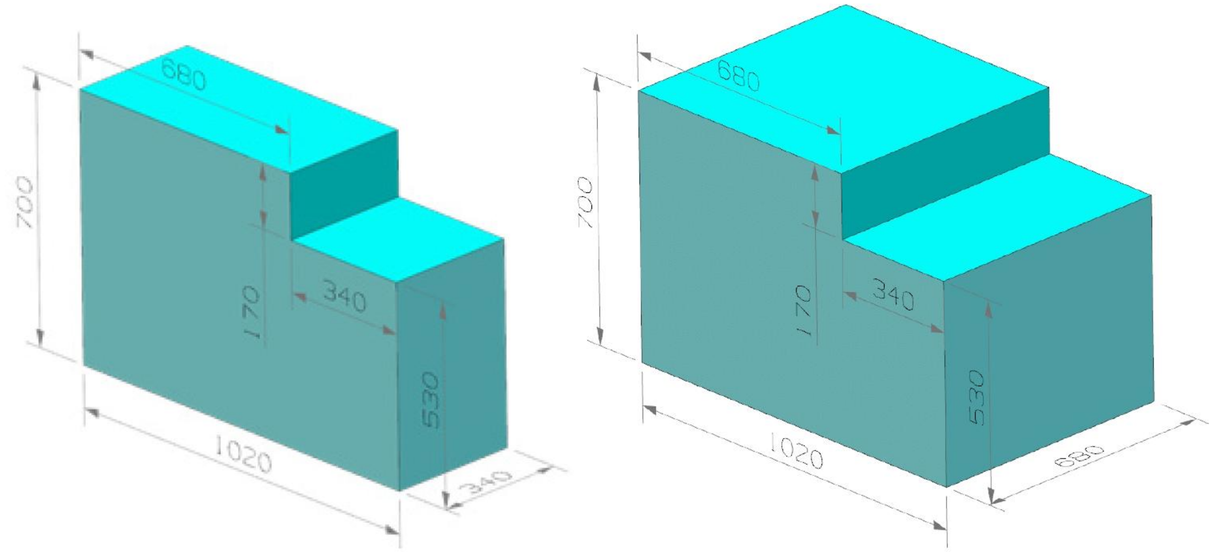


Figure 2: A and AA on their side

2.2 Standard interface definition

The interface areas and requirements for the pneumatic, hydraulic, and electronic connections are defined in the following.

2.2.1 Interface area

The interface area can be on two different sides. At least all pneumatic and hydraulic connections are within this interface area-(except eventually the drain or (box) ventilation). Sides are defined with FC module in horizontal position:

1. In corner 3, on the LxH side FC module. See Figure 3. The dimensions of the interface area will be max. 340mm x $Depth_{main}$ x Module Height
2. In corner 4, on the WxH side FC module. See Figure 3. The dimensions of the interface area will be max. 700mm x $Depth_{main}$ x Module Height

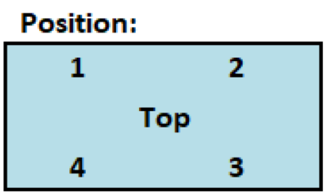


Figure 3: Top view of FCM for interface area definition

"$Depth_{main}$" or "D_{main}" is defined as the minimum depth needed to stay within the overall FC module volume (defined in D3.2), with connected male and female connectors.

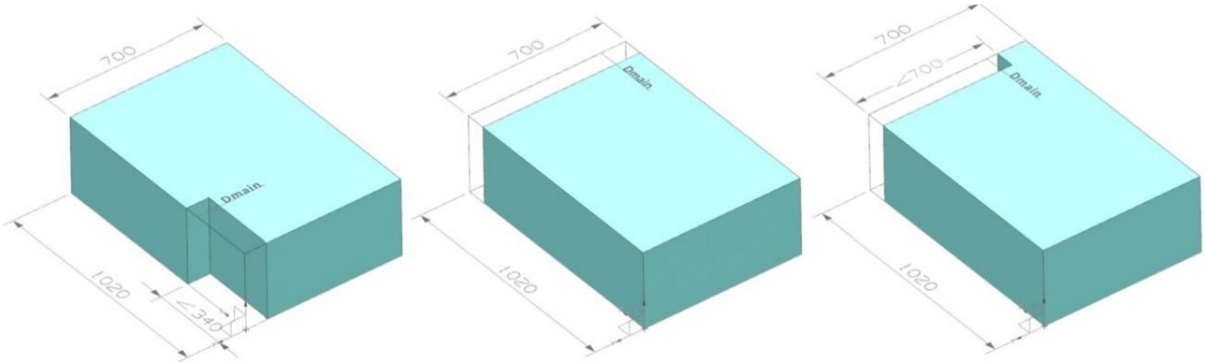


Figure 4: FCM interface areas possibility (1st side)

The size definitions of the interfacial areas can also be found in a tabulated manner in Table 2

Table 2: Dimensions FC module interface areas (1st side)

Interface 1st side	Length / mm	Depth / mm	Height / mm
A			340
AA			680
AAA			1.020
B	Max. 340	$\geq D_{main}{}^{x}$	340
BB			680
BBB			1.020
C			340

Interface 1st side	Length / mm	Depth / mm	Height / mm
A			340
AA			680
AAA			1.020
B	Max. 700	$\geq D_{main}{}^{x}$	340
BB			680
BBB			1.020
C			340

*Depth is min. Depth needed to stay within overall FC module volume with connected interfaces

Optionally, a second interface area can be utilized under the following conditions:

3. The main side complies with 1. with depth “Dmain”, and the second side complies with 2. with depth “Dsub”

OR

4. The main side complies with 2. with depth “Dmain”, and the second side complies with 1. with depth “Dsub”
5. Both connections areas are mechanically redundant, i.e., all pneumatic and hydraulic connections are on both sides (except eventually the drain or (box) ventilation)

“$Depth_{sub}$” or “D_{sub}” is defined as the minimum depth needed to stay within the overall FC module volume, with not connected male or female connectors.

Table 3: Dimensions of FC module interface areas (optional 2nd side)

Interface 2nd side	Length or width / mm	Depth / mm	Height / mm
A			340
AA			680
AAA			1.020
B	Max. 340 or 700	≥D_{sub}^{x}	340
BB			680
BBB			1.020
C			340

An exemplary image of the optional second interface area is depicted in

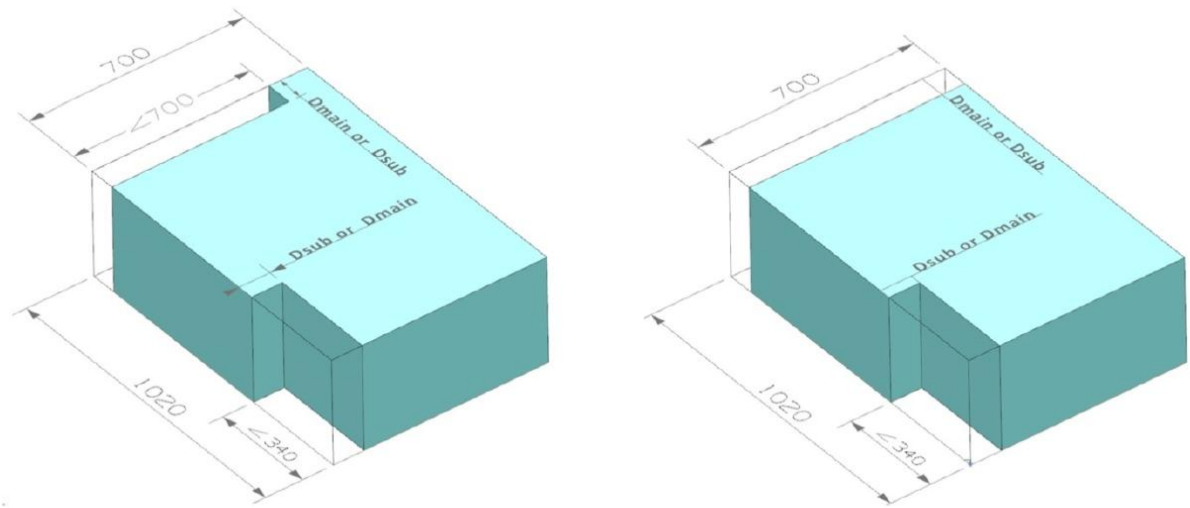


Figure 5: Example of FC module interface area with 1st side and optional 2nd side

2.2.2 Hydraulic, pneumatic, and electrical interfaces

All hydraulic and pneumatic interfaces must comply with the following conditions:

- All the pneumatic and hydraulic connections, excluding the optional drain or (box) ventilation, are positioned in the defined interfaces areas
- The connections' principle will be fixed for all FCMs but can be different depending on usage. For example, for air this can be a hose, for hydrogen a pipe. See Table 4
- The connection size ranges (in mm) are defined but will vary with the power range of the FC module Table 4.
- The electrical and I/O communication can be positioned anywhere within the chosen overall dimensions of A, B and C.

Table 4: Hydraulic and pneumatic interfaces of FC modules

	Interfaces	Inner diameter / mm Nominal power				Remark
		≤ 70 kW	71 - ≤ 100 kW	101 - ≤ 130 kW	131 - ≤ 160 kW	
Hydrogen	Pipe fitting	6-8	8-12	12-16	16-20	6-22 bar
Air	Nozzle + Hose	30-60	45-75	60-90	75-105	
Steam	Nozzle + Hose	30-60	45-75	60-90	75-105	
Drain	Nozzle + Hose	6-8	8-12	12-16	16-20	optional
Cooling FC	Nozzle + Hose	20-40	30-50	40-60	50-70	In/Out
Cooling -E	Nozzle + Hose	15-35	20-40	25-45	30-50	Optional
Breather	Banjo	M14x1.5	M14x1.5	M14x1.5	Tbd	Optional
Ventilation	Nozzle + Hose	20-40	20-40	20-40	20-40	Optional

An additional condition for the main hydraulic and pneumatic connections is that they may not interfere in the horizontal and vertical directions, see Figure 6.

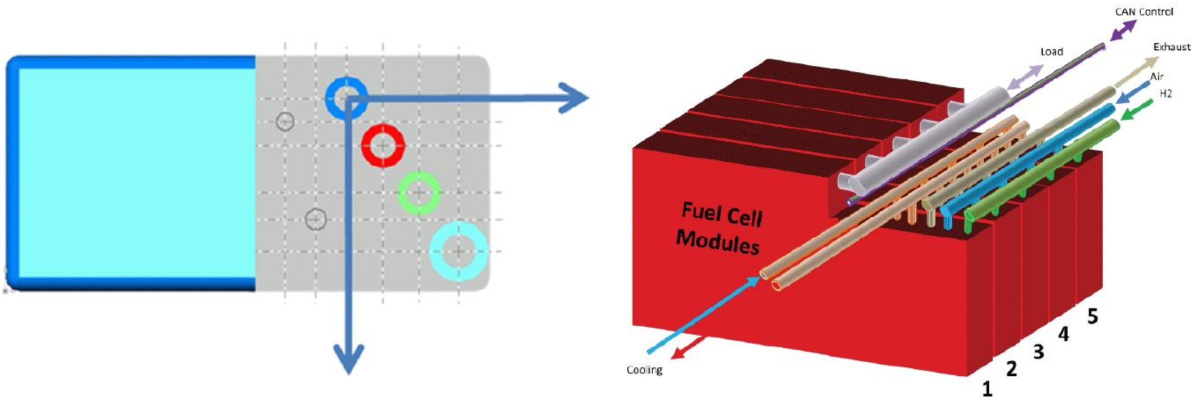


Figure 6: Non-interfering hydraulic and pneumatic connections

2.2.3 Low and high voltage connectors

Within StasHH the pins for the LV and HV connection are specified but not the specific connector.

High voltage connector:

The connector must have two pins, plus and minus. Additionally, it must withstand the maximum FCM voltage and current. Connectors already utilized in heavy-duty applications are preferred.

Low voltage connector:

The LV connector must withstand up to 100 A and cable lugs are suggested.

2.3 Standard API definition

2.3.1 Physical connector

For the physical connector for the communication with the FCM only the pins are specified and not the connector itself. It is proposed to use an 18-pin connector to include additional functions if needed.

The connector shall have at least an ingress protection level of IP54 with a proposed pinout, depicted in Figure 7.

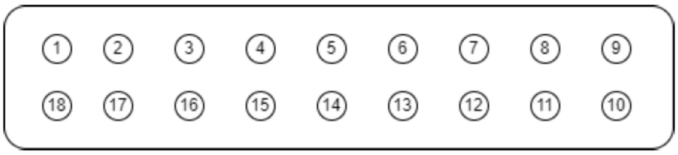


Figure 7: Pinout

The physical connector shall have enough pins to transfer all electrical signals needed and must fulfil the requirements resulting from the working environment or use case of the application.

The following pins must be included in the connector:

1. CAN ground
2. CAN high
3. CAN low
4. OPTIONAL shield
5. Wakeup signal
6. Emergency stop

The following optional pins are also specified:

7. OPTIONAL HVIL in
8. OPTIONAL HVIL out
9. OPTIONAL 24V
10. OPTIONAL ground for LV power
11. OPTIONAL CAN high for DC/DC or secondary FCM
12. OPTIONAL CAN low for DC/DC or secondary FCM
13. OPTIONAL CAN high manufacturer specific diagnostic bus
14. OPTIONAL CAN low manufacturer specific diagnostic bus

The remaining pins 15 to 18 are intended for future use and additional deployments.

2.3.2 State machine

The state machine shall at least contain the following states:

- Idle:
  In this state the FCM has LV power sufficient to activate the FCCU. This state corresponds to “Power on” in J1939. Periodic counter messages are transmitted
- Standby:
  No HV output power but necessary subsystems are powered and ready such that it can start producing output within a short time. Error and diagnostic messages can be sent
- Starting:
  FCM is transitioning from standby to running state. Power is ramping up and HV bus is enabled – Module can consume and provide energy
- Running:

FCM is active and delivering power. Power may be limited due to derating which will be indicated by FCM

- Stopping:
  FCM is ramping down and returning to standby state. HV bus must be enabled during shut-down procedures.
- Error:
  Error state must be enabled from any other state. FCM shall be brought in a safe state

Proprietary substates can be defined by the FCM manufacturers.

For further information see D3.4 document.

2.3.3 Messages

In the following the messages that are used in the communication between the application ECU and FCCU are listed:

- State machine control
- State machine feedback
- Emergency stop request
- Reference power value
- FCM actual current and voltage
- Power limits
- Voltage limits
- High voltage bus information
- FCM temperature
- Time and date
- Ambient conditions
- Vehicle speed
- FCM gas leakage
- Alarm messages

For a generic description of the messages including a mapping to a J1939 message, please refer to the official D3.4 document.

3 Design of Freudenberg

Freudenberg e-Power Systems is a leading provider of electrical power solutions for the global heavy-duty markets. Based on Freudenberg 's long-term experience in fuel cell technologies, we combine component knowledge with a holistic system understanding. In order to serve heavy-duty applications, our fuel cell systems are designed for best-in-class total cost of ownership. The unique design serves the sole purpose of fulfilling the needs of heavy-duty customers and end-users: a long and low-maintenance lifetime combined with consistently high overall efficiency.

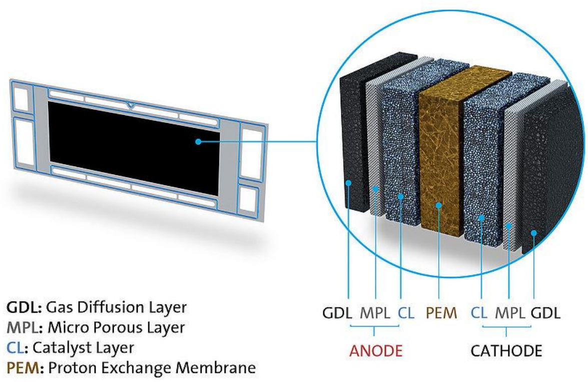
Due to our unique vertical integration, cell-level expertise, technical excellence, and holistic understanding of the entire value chain, we are the ideal partner for our customers, helping to achieve profitable growth and meet net-zero targets.

3.1 True Heavy Duty Fuel Cell Technology

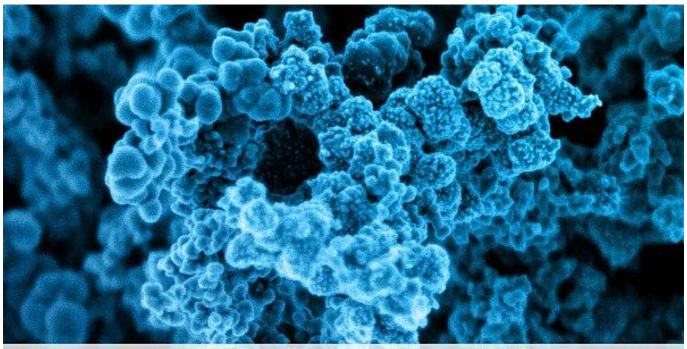
The heart of each fuel cell system is the fuel cell stack. When the stack has a true heavy-duty design, it determines the efficiency and operational lifetime of the complete system. Our SMARTR heavy-duty stack platform is designed and produced with our unique vertical integration. Starting from the cell level, the selection of raw materials, and the proper component configuration result in a unique level of technical performance.

3.1.1 MEGA - Membrane Electrode Gasket Assembly

Robust, stable, durable, and resilient to hydrogen impurities, our membrane electrode gasket assemblies (MEGA) are ideal for fuel cell systems powered by pure hydrogen or reformate. In our proprietary MEGA designs, we combine manufacturing technologies with component expertise to maximize the operational lifetime and performance of our fuel cells while producing the assemblies in a cost-efficient and scalable way.



Our proprietary catalyst production enables low manufacturing cost while ensuring superior efficiency and an extraordinary lifetime through highly reactive and long-lasting catalyst layers. To boost the performance and durability of our catalysts, we have developed a next-generation catalyst nanostructures, including core-shell and alloy particles, using a patented manufacturing process compatible with our highly cost-efficient roll-to-roll technology. This enables us to for high-volume industrialization at competitive prices, while our use of platinum solution as a raw material, instead of using standard catalyst-coated membranes, offers significant cost reductions.



Highly Reactive and Robust Catalyst Layers, for Best-in-class Fuel Consumption

3.1.2 Graphite Bipolar Plates

For long-term resistance against chemical stress on the cell level, our graphite bipolar plates are the right solution. They are designed to withstand harsh conditions occurring due to the electrochemical reactions in the cells. This is a huge advantage over metal bipolar plates, which are unable to handle heavy-duty lifetimes and are subject to corrosion. Our graphite bipolar plates last more than 100,000 hours, also support high efficiency and robustness with an innovative cooling concept on cell level.

3.1.3 Advanced Cell Design

The SMARTR stack has a unique temperature distribution on cell level across the complete stack by a cooling water spread of 10 degrees Celsius, enabling the system to maintain efficiency while performing in challenging environments and situations without compromising on lifetime

The unique cell cooling results in a narrow temperature distribution of only 5 degrees Celsius which helps avoid accelerated degradation from thermal stress, the number one factor impacting lifetime and efficiency.

This feature allows for temporary overheating of the cells in challenging situations, such as a truck driving up or downhill with a full load, without compromising on the operational lifetime or overstressing the vehicle's cooling system. The result is full power output and best-in-class fuel efficiency, as well as a compact and cost-efficient cooling system for heavy-duty vehicles.

3.2 Key technical specifications

Freudenberg develops our fuel cell module according to standard Size AA with a power class of 120 kW. The Freudenberg module respects all StasHH key requirements and is expected to be available on the market soon.

The Freudenberg Fuel Cell module is designed to be used in several heavy-duty applications and consists of a module which includes a true heavy-duty fuel cell stack and the associated Balance of Plant to operate the stack and provide the electrical power to the application.

The key technical specifications are listed in Table 5.

Table 5: Mandatory technical specifications of FCM according to StasHH

Requirement	StasHH requirement	Freudenberg
Service life / h	> 15.000	> 35.000h
Geographical heights / m	< 3.000m with derating	< 3.000m with derating
IP class	> IP54	Equivalent to IP67
Low voltage / V	24DC	24DC (ISO 16750 - II)
High voltage output / V	160 – 850 DC	450 – 800V
Operational ambient temperature / °C	-25 to 45	-30 to 45 °C
Conductivity glycol / µS/cm	< 6 (ASTM D 1125	≤ 5µS/cm
H_2 input pressure / bar	6 – 22	15 +/- 2 bara
Hydrogen quality	ISO 14687 or SAE J2719	SAE J2719

Additional technical specifications of FCM are listed in

Table 6: Additional key technical specifications of FCM

Requirement	FCM
Net continuous system power output Pnet BOL / kW	120 kW
DC/DC included in FCM / -	Scope of delivery
System efficiency at Pnet BOL	> 50% (incl. DCDC) @ nominal power

The information provided herein and below constitutes only an excerpt from our specifications. For further clarification, please do not hesitate to contact us directly. We are at your service

3.3 Exterior design

The exterior design of the FCM with all main dimensions is shown in Figure 8.

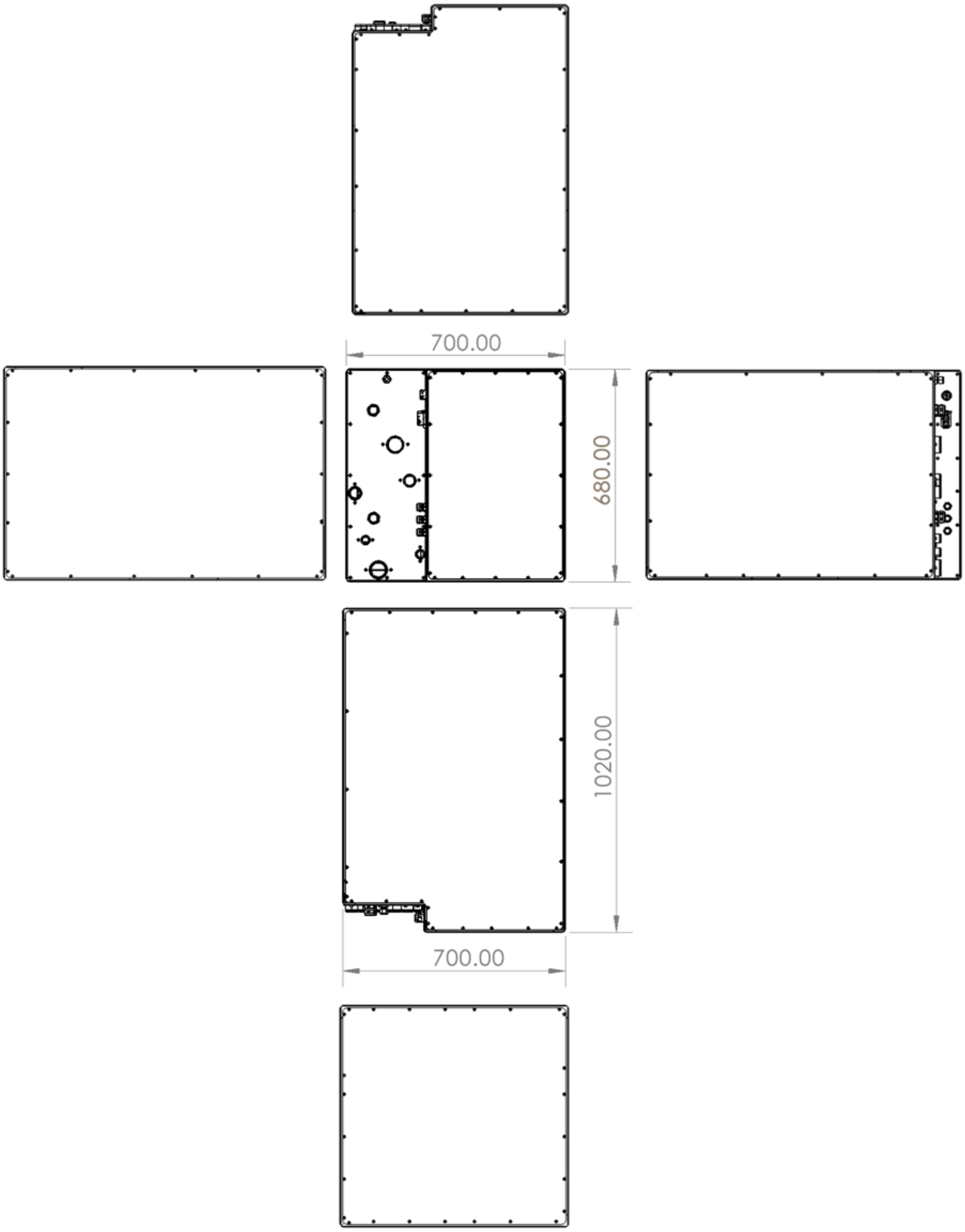


Figure 8: Exterior design with main dimensions of FCM]

3.4 Interface specification and area

3.4.1 Interface area including hydraulic and pneumatic interfaces

The design and dimensions of the interface area is depicted in Figure 9

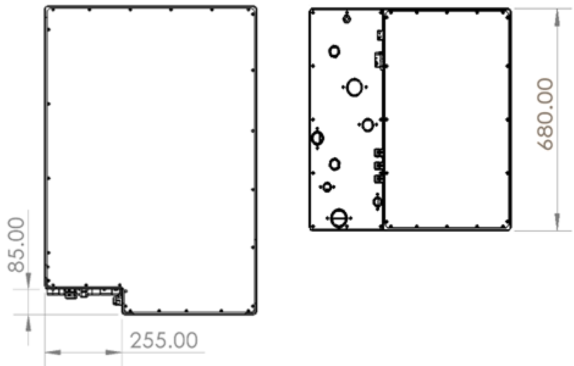


Figure 9: Main interface area of FCM

The positioning of the pneumatic and hydraulic connections of the FCM within the interface area are shown in

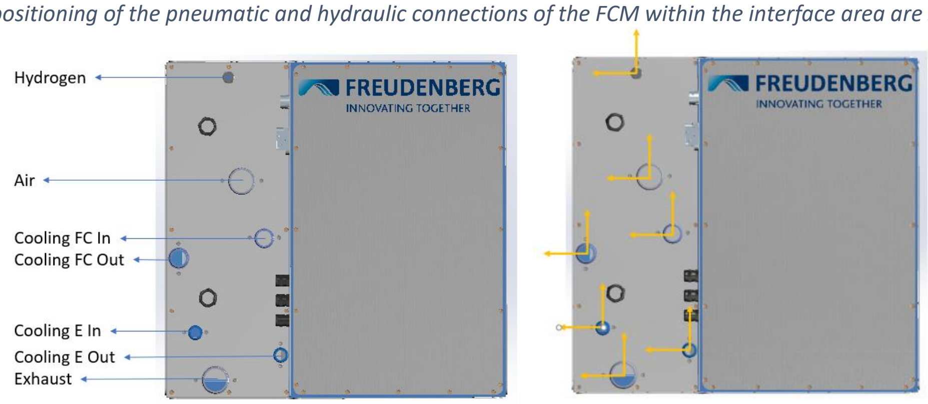


Figure 10. The pneumatic and hydraulic connections do not interfere in vertical and horizontal directions as also shown in

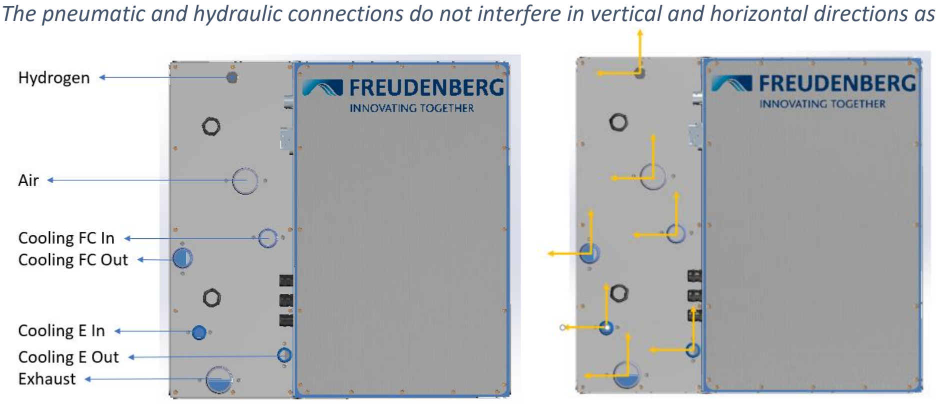


Figure 10. The specifications of the interfaces are summarized in Table 7.

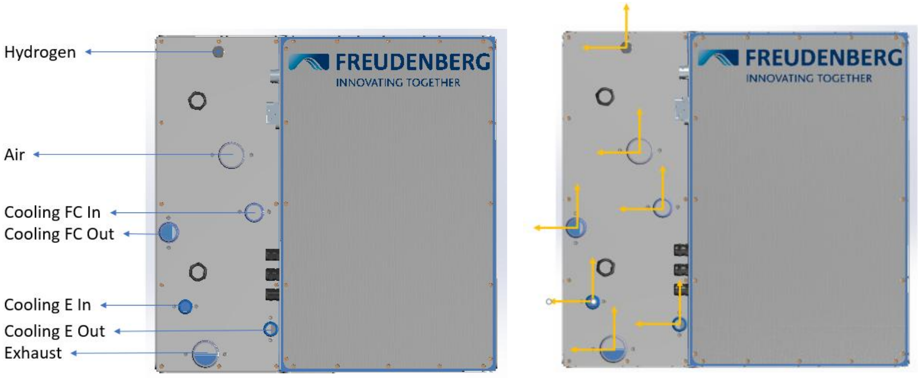


Figure 10: Position of hydraulic and pneumatic connections of FCM

Table 7: Specifications of hydraulic and pneumatic interfaces

	Interface type	Inner diameter / mm
Hydrogen	Stainless steel 2-ferrule fitting	In Ø 12 mm
Air	Nozzle + Hose	In Ø 45 mm
Steam	Nozzle + Hose	In Ø 45 mm
Drain	n.a.	
Cooling FC	Nozzle + Hose	In Ø 30/30 mm
Cooling -E	Nozzle + Hose	In Ø 20/20 mm
Breather	n.a.	
Ventilation	n.a.	

3.4.2 Electrical interfaces

3.4.2.1 LV

The LV connectors are placed on the interface area of the FC module.

Freudenberg offers customized solutions for the LV power supply connector based on different market-available heavy-duty connectors.

3.4.2.2 HV

The HV-Connections are placed on the interface area of the FC module.

Freudenberg offers customized solutions for the HV power connector based on different market-available heavy-duty connectors.

3.4.2.3 Communication

The Communication connector is placed on the interface area of the FC module.

The communication connector is a heavy-duty connector, as specified by the standard.

3.5 API definition

The Communication Protocol to application is based on the SAE Standard J1939 and implemented according to StasHH Standard.