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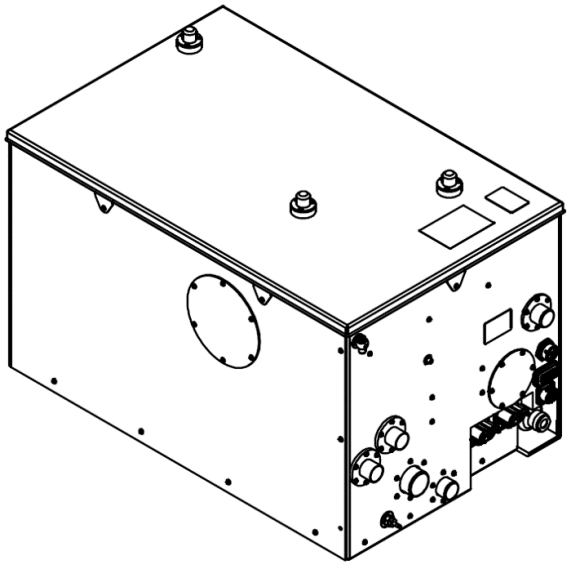
Final design of Nuvera FCM



Clean Hydrogen Partnership

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Towards a standardised fuel cell module

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1 Introduction

Nuvera Fuel Cells has selected the module HH_{AA} delivering a maximum net unregulated power equal to 59 kW with all interfaces placed on the side with smallest area WxH as defined in par. 2.2.1. This module is mostly intended for medium and heavy duty applications but naval, train and stationary are other potential applications.

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 different 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.

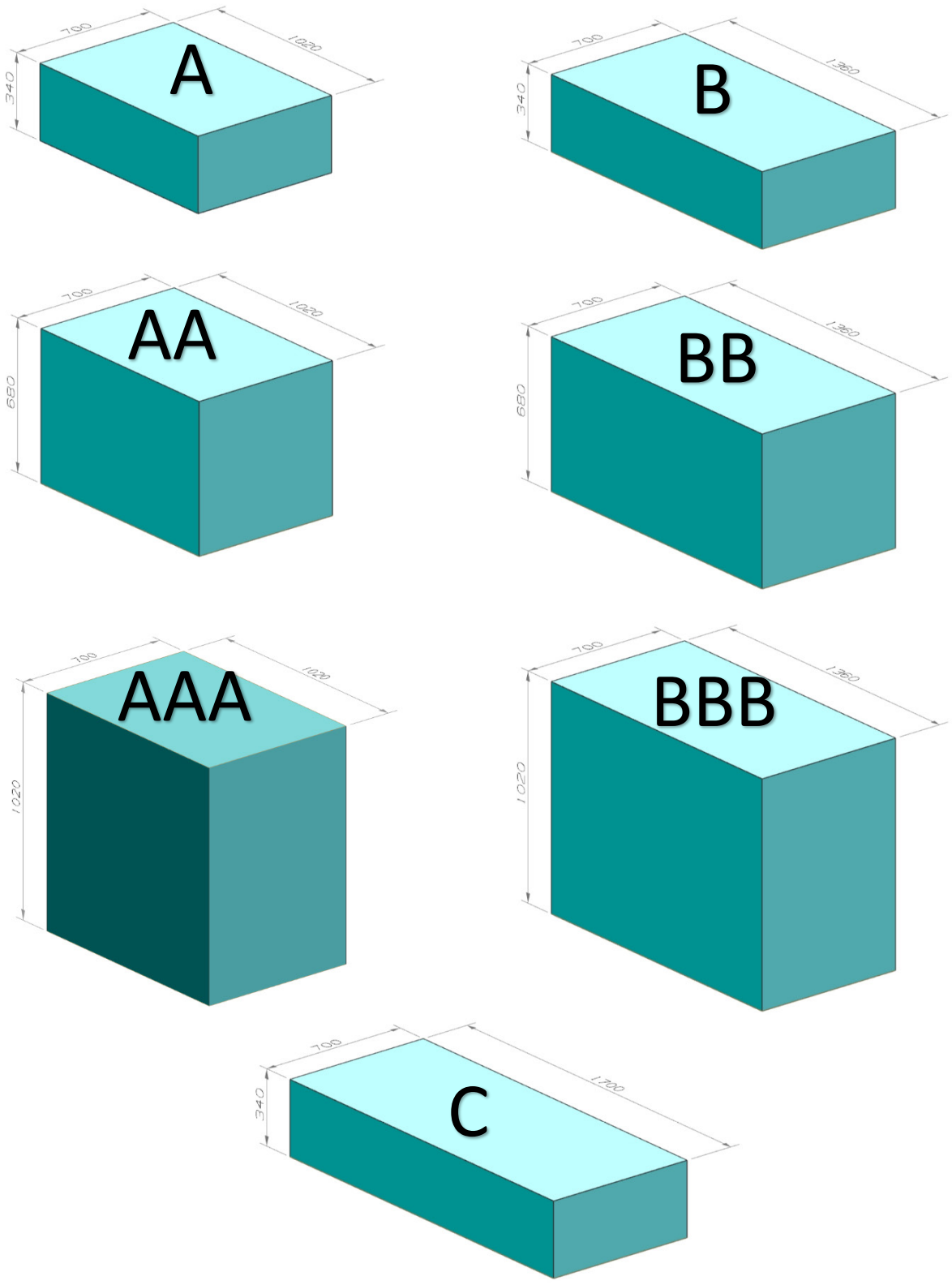


Figure 1: FC modules A, B and C

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

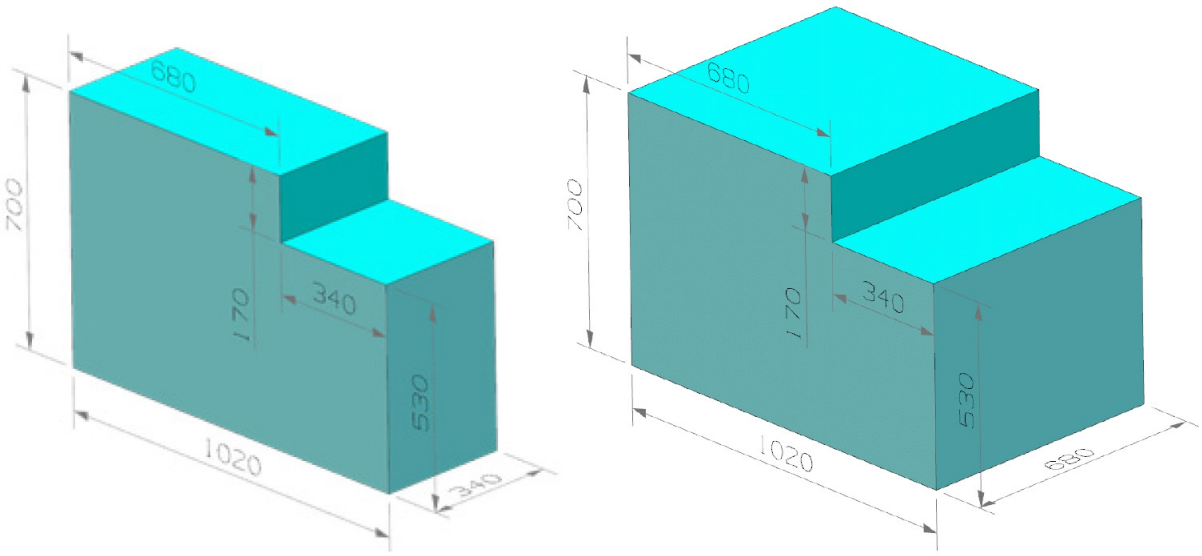


Figure 2: A and AA on their side

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

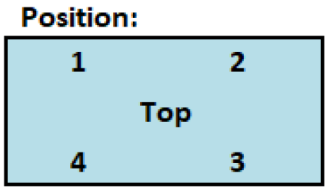


Figure 3: Top view of FCM for interface area definition

"$Depth_{main}$" 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.

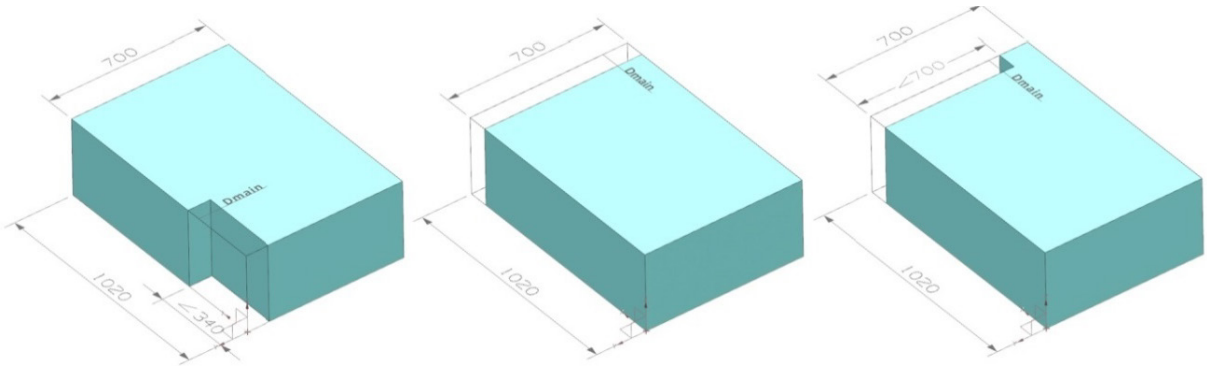


Figure 4: FCM interface areas possibility (1st side)

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	Max. 340	≥D_{main} x	340
AA			680
AAA			1.020
B			340
BB			680
BBB			1.020
C			340

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

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

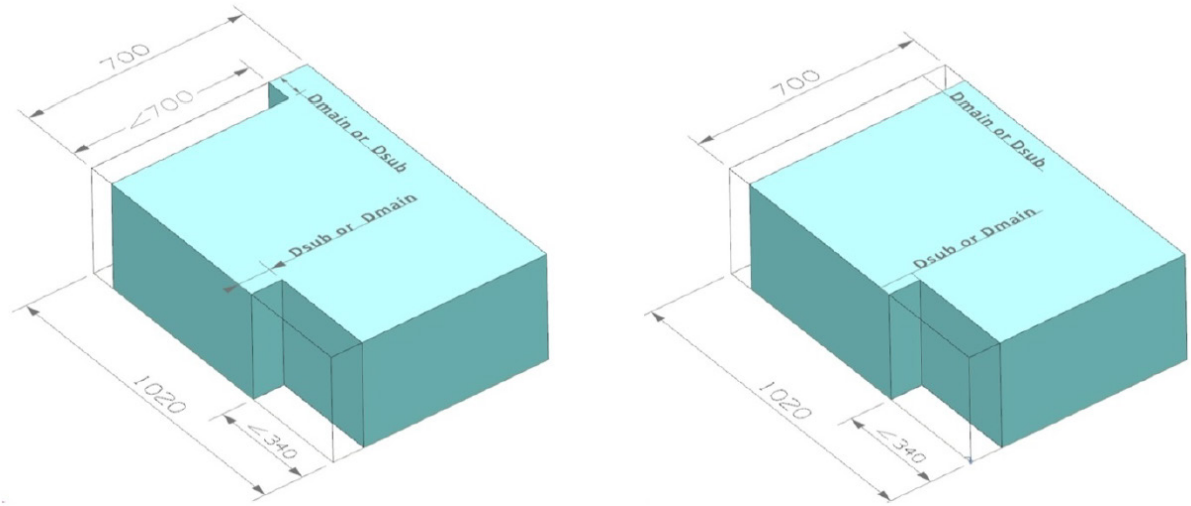


Figure 5: Example of FC module interface area with 1st side and optional 2nd side

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.

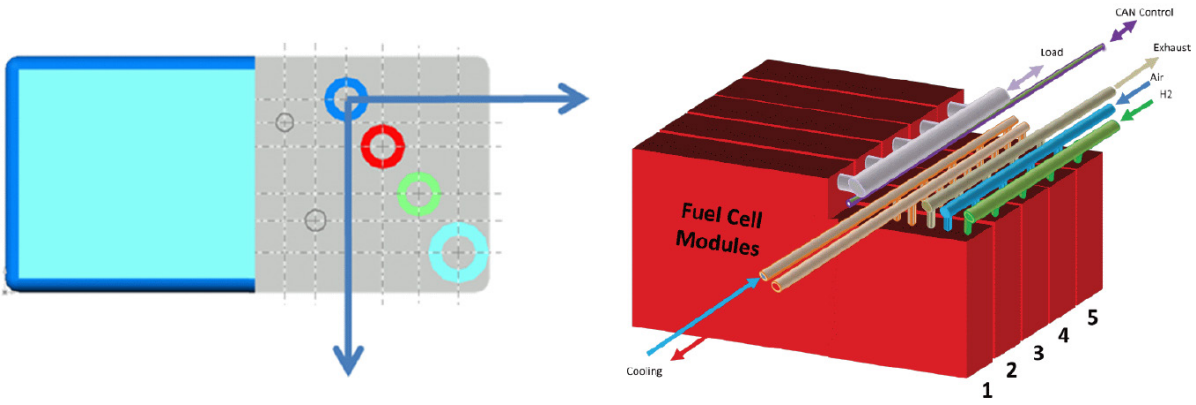


Figure 6: Non-interfering hydraulic and pneumatic connections

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 of

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

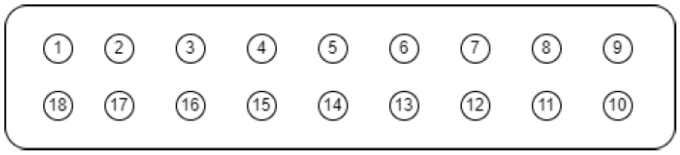


Figure 7: Pinout

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 additionally 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 Nuvera

The Nuvera module meets the HH_{AA} standard size, with all interfaces on the WxH side and is delivered with a cover. The intended application is medium and heavy duty vehicles but rail, naval and stationary applications are other potential applications.

3.1 Key technical specifications

The mandatory key technical specifications are listed in Table 5.

Table 5: Mandatory technical specifications of FCM according to StasHH

Requirement	StasHH requirement	FCM
Service life / h	> 15.000	>15000 hrs
Geographical heights / m	< 3.000m with derating	< 3000m with derating above 1000m
IP class	> IP54	IP65 TBC
Low voltage / V	24DC	24VDC
High voltage output / V	160 – 850 DC	175-290 VDC BOL
Operational ambient temperature / °C	-25 to 45	-30°C to +45°C
Conductivity glycol / µS/cm	< 6 (ASTM D 1125	<= 5
H_2 input pressure / bar	6 - 22	12.5 to 15.0 bar absolute
Hydrogen quality	ISO 14687 or SAE J2719	ISO 14687 or 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 P_{net} BOL / kW	59 kW
Net continuous system power output P_{net} EOL / kW	45 kW
Weight / kg	210kg
DC/DC included in FCM / -	No
Peak system efficiency / %	57%
System efficiency at P_{net} BOL	48%
System efficiency at P_{net} EOL	38%
Gravimetric system power density @ BOL / kW/ton	28.1 kW/ton
Volumetric system power density @ BOL / kW/m³	160.9 kW/m³

3.2 Exterior design

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

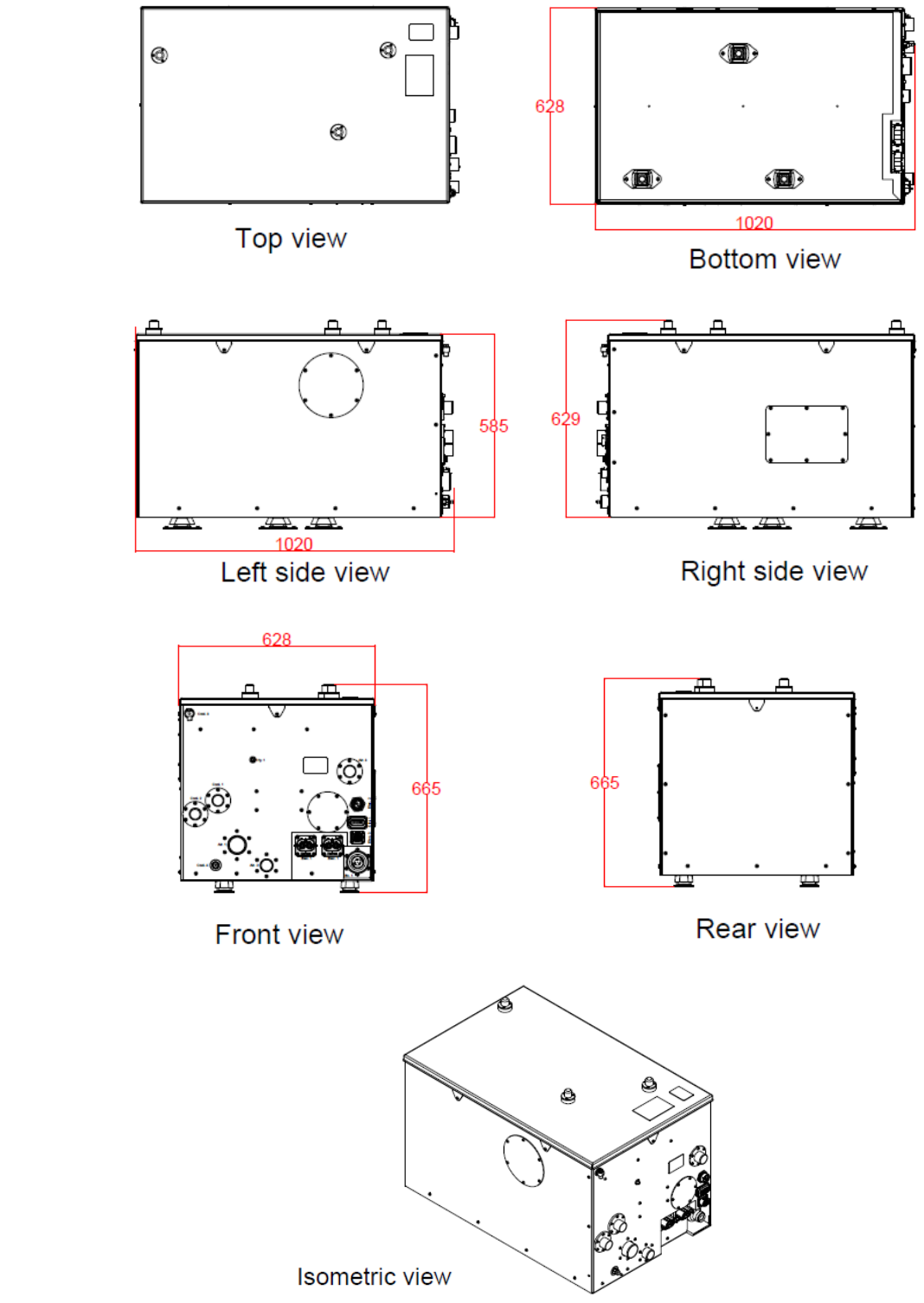


Figure 8: Exterior design with main dimensions of FCM [please add CAD images of all sides to verify compliancy to StasHH]

3.3 Module Pictures

Pictures of the module built for testing shown in Figure 9.

Figure 9: Pictures of the FCM Module built for testing

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 10

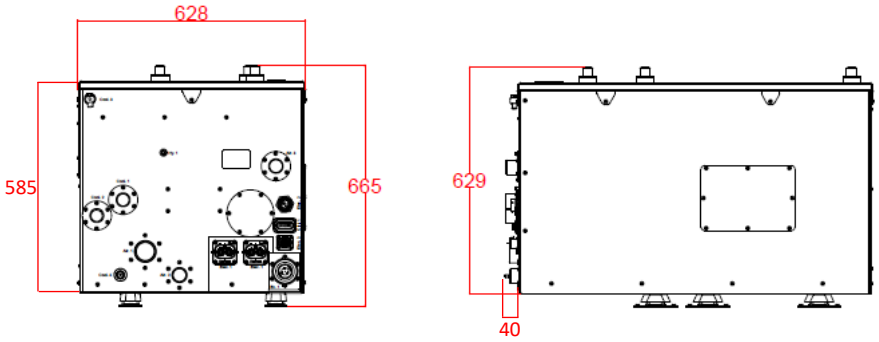


Figure 10: Main interface area of FCM

The positioning of the pneumatic and hydraulic connections of the FCM within the interface area are shown in Figure 12. The specifications of the interfaces are summarized in Table 7.

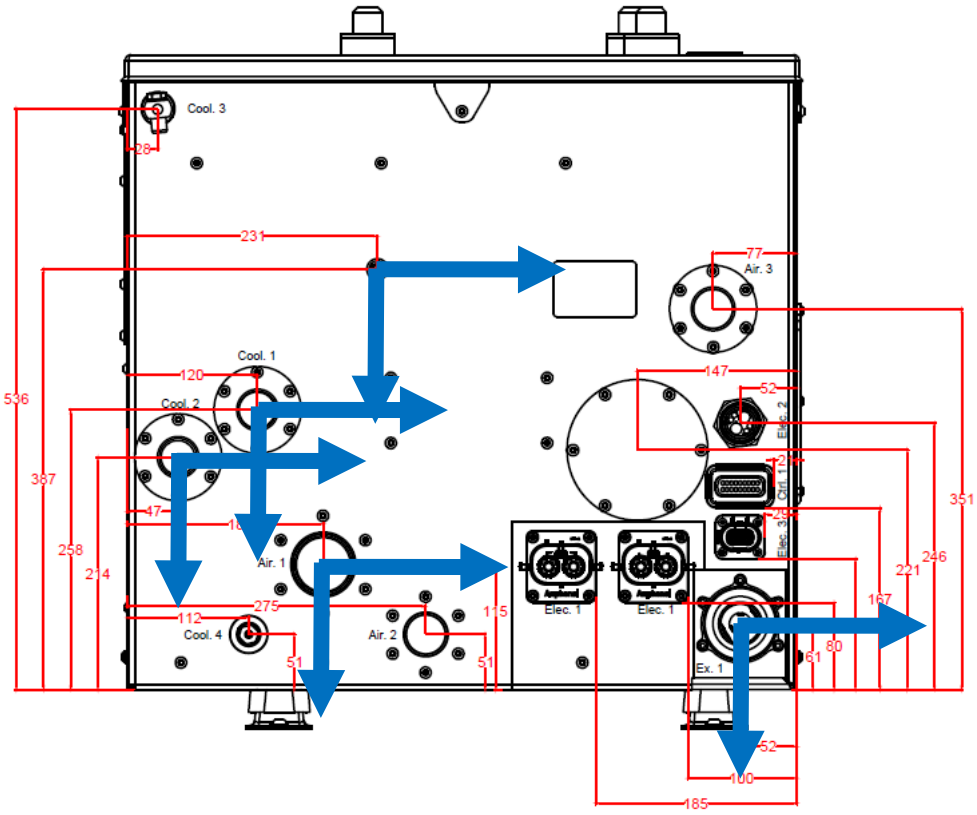


Figure 11: Position of hydraulic and pneumatic connections of FCM

Table 7: Specifications of hydraulic and pneumatic interfaces

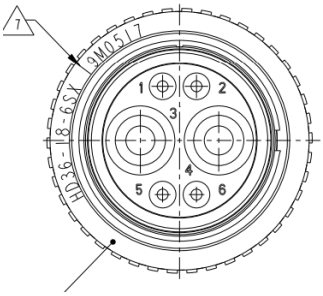
	Interface type	Inner diameter / mm
Hydrogen		7 mm
Air		52 mm
Steam		37 mm
Drain		7 mm
Cooling FC		36 mm
Cooling -E		N/A
Breather		M14 x 1.5
Ventilation		36 mm

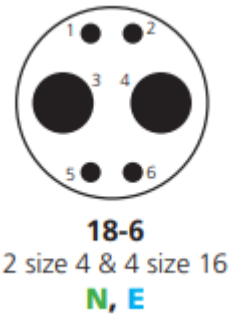
3.4.2 Electrical interfaces

Within this chapter the electrical interfaces and specification of the connectors are summarized.

3.4.2.1 LV

Low Voltage connector is a Deutsch connector, HD Series, 18-6 configurated, mounted on the WxH side of HH_{AA}, on the same surface of the Hydraulic connections. 4 AWG (13 mmq) connector pins are able to provide up to 100 A at 27 Vdc.

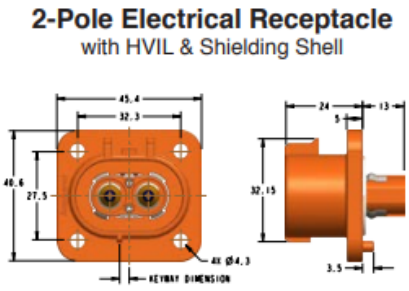




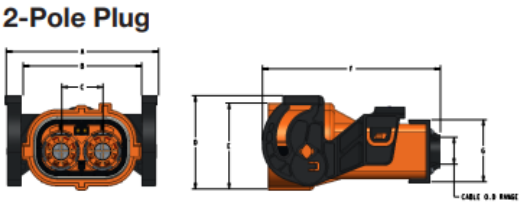
3.4.2.2 HV

HV connection is composed of three different connectors, all mounted on the WxH side of HH_{AA}, on the same surface of the Hydraulic connections:

a) Amphenol ePower-Lite series connector, 2 pole, 6 mmq, with HVIL, in order to supply air compressor;
b) Amphenol UPC series connector, 2 pole, code A, 50 mmq, with HVIL, in order to draw power from the stack (plus, +);
c) Amphenol UPC series connector, 2 pole, code B, 50 mmq, with HVIL, in order to draw power from the stack (minus, -);



ePower-Lite connector



UPC connector

3.4.2.3 Communication

Controls interface connection is done through a TE connectivity 18 pins connector, Heavy Duty Sealed Connector Series, mounted on the WxH side of HH_{AA} , on the same surface of the Hydraulic connections.

The connector will receive following signals:

- Key ON (wake-up);
- HVIL;
- E-STOP;
- 24V;
- CAN-H;
- CAN-L;
- CAN-H (debugging);
- CAN-L (debugging);
- CAN-H (programming);
- CAN-L (programming)
- GND

3.5 API definition

The Nuvera® FCM requires CAN communication for operation. FCM control parameters and status information is broadcast, and system controller messages must be received.

Interface
Frame Format: Extended 29-bit Identifier (CAN 2.0B)
Physical Layer Baud Rate: 500kbps

Operating Modes
The FCM has the operating modes described below in Table. The FCCU will communicate its current operating mode in CAN messages.

Mode	Description	FCM Status
Depowered	FCM is completely OFF. All power and communications between the FCM and APPLICATION system are OFF. The FCCU is depowered and the FCM valves and other components are in their default depowered positions.	• Depowered • Communications OFF
Sleep	The FCM is in a low-power-consumption state with the fuel cell and process components OFF. The BOP power to the FCM controls is ON and the FCCU is using a minimal amount of power to monitor the Key-On signal. When the Key-On signal is enabled by the application ECU, the FCU will move from the *Sleep* mode to the *Standby* mode.	• Fuel Cell OFF • BOP Elec.2 power ON • FCCU in sleep mode • Communications OFF
Standby	The fuel cell is OFF and the FCM is awaiting a signal to start the fuel cell. The FCCU and BOP are powered ON. CAN communications between the FCM and APPLICATION system are ON. The FCM enters standby mode when the Key-On signal is enabled or when the application ECU requests that the FCM enter Standby mode (which may first take the FCM from the *Run* mode through the *Shutdown* mode before entering the *Standby* mode). During the *Standby* mode, the application system must provide BOP power and signals needed for the FCM.	• Fuel Cell OFF • FCCU and BOP power ON • Communications ON
Startup	FCM enters *Startup* mode when it receives a request to run and no critical faults are detected. The FCCU controls the BOP components to prepare the FCM to produce power. During the *Startup* mode, the application system must provide the external fluids, power, and signals needed for the FCM.	• Fuel Cell starting • FCCU and BOP power ON • Communications ON
Run	FCM enters Run mode after it successfully completes the Startup mode and no critical faults are detected. The FCCU controls the BOP to allow the fuel cell to provide power to the APPLICATION system power module. The FCM continuously broadcasts the available	• Fuel Cell producing power • FCCU and BOP power ON • Communications ON

	current and current ramp rates. The APPLICATION system power module must respect the communicated limits. The FCM also broadcasts signals that the APPLICATION system thermal module must use to properly control the coolant temperature. During the Run mode, the APPLICATION system must provide the external fluids, power, and signals required by the FCM.	
Idle	The Idle mode is a form of Run mode. Running the FCM with zero (or near zero) net power production is described as idling. All conditions described in the Run mode apply including the requirements for the APPLICATION system.	• Fuel Cell producing power • FCCU and BOP power ON • Communications ON
Shutdown	FCM enters Shutdown mode when it receives a request to shut down (Start command cleared) or when a fault condition requires the FCM to shut down. During Shutdown, the FCM communicates that the available output current is zero and the ECU controls the BOP to prepare the fuel cell for either the Standby or Depowered modes. During the Shutdown mode, the APPLICATION system must continue to provide the external fluids and signals required and the APPLICATION system power module must not draw power from the FCM.	• Fuel Cell shutting down • FCCU and BOP power ON • Communications ON
Fault	The Fault mode is entered when the FCM detects a fault condition. The fuel cell is turned OFF per the normal shutdown procedures and the FCM pauses briefly in the Fault mode with the ECU powered ON. Depending on the fault classification, the FCM will return to the standby state or lock out and/or depowered. Note if a Major fault or E-Stop occurs, the FCM may depower immediately without entering the Fault mode.	• Fuel Cell OFF • FCCU and BOP power ON • Communications ON
Diagnostics	The Diagnostic mode can be accessed by authorized service personnel.	• Fuel Cell controlled • FCCU and BOP power ON • Communications ON

Messages
Messages will be sent according to StasHH DBC. Messages sent will be:

- MG1IS1
- MG1ILAP
- MG1IMT
- MG1IMF1
- MG1IR1
- MG1IR2
- DM1

3.6 Design adaptation after testing

No design adaptation had to be done after testing. Further design modification has been done to make the final mechanical design in line with the standard. The total length has been reduced because the original prototype exceeded the maximum length defined in the StasHH standard.