The StasHH Fuel-Cell Module Standard

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***Abstract*—This paper describes and motivates a standard for heavy-duty hydrogen fuel-cell modules in terms of their form factors and interfaces, both physical and digital. The goal is that the standardised fuel cell modules shall be suitable for multiple applications such as ships, trains, stationary generator sets in addition to heavy duty vehicles. While standards have been developed for test protocols, safety, and fuelling operations, little to no work has been done to define an interchangeable standard for fuel-cell modules. Such a standard can prove decisive to pool several heavy-duty markets together, accelerate design and realisation of hydrogen vehicles, enable competition among fuel-cell module manufacturers, and reduce their total cost of ownership. The StasHH project is developing prototypes from eight major manufacturers and will test them during 2023.**

***Index Terms*—fuel cell, module, standard, size, interface, digital**

I. Introduction

Standardisation of fuel-cell (FC) systems is the key to kickstart their deployment in the heavy-duty (HD) sector.

FC applications have been deployed for almost every HD vehicle available, from buses to trucks, from ships to aircraft. However, these projects, including commercial deployments such as Alstom's iLint train, rely on original equipment manufacturers (OEMs) and FC system manufacturers to engineer the complete vehicle from the ground up. The vehicle chassis and the FC system must therefore be engineered around each other, by two cooperating teams that can be located on different continents, and the resulting work is hardly reusable in the next project, much less on a competitor's chassis.

The consequence of this state of affairs is that HD FC vehicles have long development times, have difficulties achieving economies of scale, do not benefit from competition as FC suppliers and OEMs are bound to each other, increasing their cost and slowing their adoption. Standardisation of HD FC systems can go a long way to boost their viability in the market. In particular, it can:

- Pool all HD OEMs in a single large market for HD FCs;
- Reach MW scale with modular units, covering even more OEM sectors;
- Enable fair competition between FC suppliers, removing vendor lock-in;
- Reduce development and innovation costs for OEMs, lowering the entry threshold;
- Improve the supply chain with fewer FC models, giving higher reliability;
- Enable automation of mass production;
- Reduce total cost of ownership, which is far more important for commercial HD users than for consumers of luxury cars (e.g. Tesla).

The **StasHH** project is funded by the European Commission with the task to establish standards for size and interfaces (physical and digital) of HD FCs. According to StasHH' definition, a fuel-cell module (FCM) contains the FC stack, air compressors, humidifiers and other balance-of-plant (BoP) units, but not hydrogen storage and radiators; DC/DC converters can be optionally included in the FCM.

Current standardisation efforts within hydrogen technologies are ongoing at several standardisation bodies:

- IEC TC 105 "Fuel cell technologies" is strongly focused on safety and test protocols;
- ISO TC 197 "Hydrogen technologies" concerns mostly hydrogen fuel, tanks and stations;
- CEN CLC/JTC 6 "Hydrogen in energy systems" works on nomenclature, guarantees of origin and safety.

None of these has developed or plans for standards for the shape, interfaces or other technical properties of FCMs: in fact, all HD-FC deployments to date have had to be custom-engineered, with minimal capability for reuse in other applications.

There has not been much previous standardisation activity for FCM digital communication interfaces either. However, it can be noted that researchers have proposed to base the communication for a specific fuel cell vehicle on CAN bus and SAE J1939 standards, which are widely used in heavy duty vehicles [1]; at that time the proposed communication was limited to a single message to set current and voltage, and to switch the fuel cell and the DC/DC converter on and off. The StasHH standard is based on CAN bus and updated J1939 specifications and includes more functionality. Within the automotive industry there is an initiative to standardise the software architecture for ECUs, in the AUTOSAR development partnership. It has been described how the AUTOSAR

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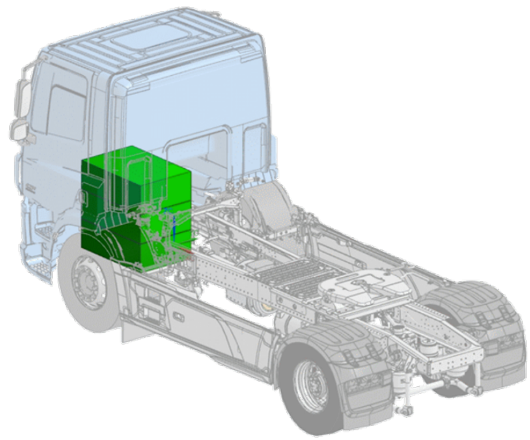

Fig. 1. The volume available in the engine bay of a European truck.

architecture and related toolchain can be used to develop an energy management system for a fuel cell vehicle [2]. The development methodology allows system constraints to be imported in a DBC file to be used in the system level development. The StasHH standard is provided with a DBC file to work smoothly with existing toolchains and simplify the integration of standardised FCMs.

The StasHH consortium comprises 8 FCM suppliers (Ballard, Freudenberg, Hyundai, Intelligent Energy, Nuvera, Plastic Omnium, Proton Motor, and Toyota) and OEMs from all sectors (Alstom, AVL, Fincantieri, Damen, Future Proof Shipping, Solaris, VDL and Volvo). The standard has been defined in 2021; in 2022–2023, the FCM suppliers will build their prototypes, which project partners TNO and FEV will test in 2023–2024.

The contribution of this paper is to address the lack of a standard for FCM and present an overview of the proposed StasHH standard with its form factors, physical and digital interfaces and the rationale for the design. The proposed standard will be updated during the project, feedback and input from a wider community is therefore welcome.

II. Form Factors

The physical size of the StasHH standard is dictated chiefly by the available dimensions in an European truck, which was identified as one of the most challenging environments to install an FCM due to the tight spaces induced by EU regulations. An European truck can install a FCM either in the diesel tank areas on either side, between the front and hind wheels, or in the engine bay (see figure 1). We found that a maximum height of 680 mm and a maximum width of 700 mm would be almost universally supported for the diesel tank area, with length strongly depending on the specific vehicle. Engine bay measures vary among manufacturers, but a box with measures 700 mm$\times$1360 mm$\times$1020 mm is acceptable to most.

StasHH defines three basic form factors with different length, but same width and height; assuming a unit length of 340 mm, the StasHH standard form factors are 1 in height, (slightly more than) 2 in width, and either 3, 4 or 5 in length for respectively types A, B and C (an eventual D would simply be 2 A's). These form factors are listed in table I and pictured in figure 2.

TABLE I
THE STANDARD BASIC SIZES AND SOME COMMON COMPOSITE SIZES.

Type	Height	Width	Length	Volume
	....	mm	....	dm^3
A	340	700	1020	243
B	340	700	1360	324
C	340	700	1700	405
AA	680	700	1020	486
BB	680	700	1360	647
BBB	1020	700	1360	971

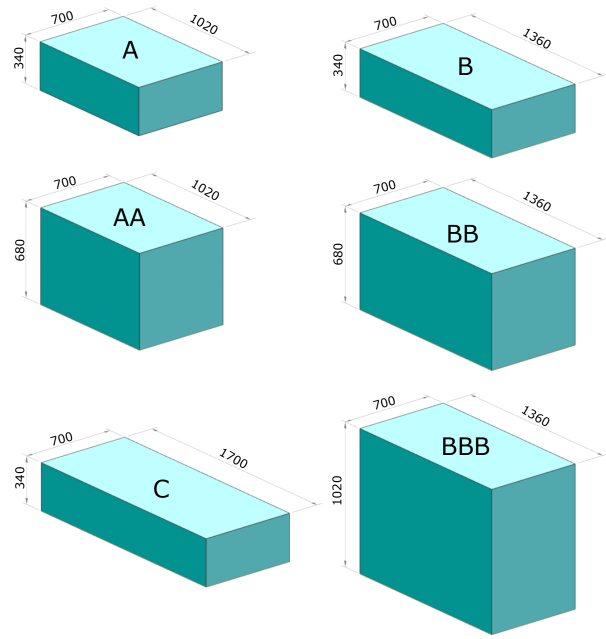

Fig. 2. The StasHH FCM sizes; measurements in mm.

Form factors are not tied to a specific range in power capability, as long as it is above 30 kW; tolerances are +0/−100 mm. Optionally, units can be oriented on the side, but it is not required that units shall function in more than one nominal orientation.

Form factors can be combined by stacking multiple units: AA is for example two A volumes on top of each other, and BBB is three B volumes. Currently, industry feedback within the StasHH consortium seems to favour A and B form factors, with composites AA, BB and BBB also being popular. Composite units in length are indicated prepending a number, e.g. 2A or 2BB. No interest has been received for composite units stacked along the volume's width.

Some form factors have been identified as especially appropriate for the following applications:

- **Truck:** Engine compartment: BBB; diesel-tank compartment: 2AA or BB; Underfloor auxiliary power unit: A, B or C.

- **Bus:** Engine compartment: AA or BBB; roof or underfloor C, 2A, 2B or 2C.
- **Wheel loader:** Engine bay: BBB.
- **Small ships:** Engine compartment: BB or BBB.
- **Inland and coastal ships:** Engine compartment: A or AA in racks.

III. Physical Interfaces

StasHH's standard defines some general areas where the physical interfaces can be located, but does not define in detail the position of each connector, its exact size or its shape, which are left to the manufacturers to decide; this because moving a hose by a moderate length or employing an adapter are not considered major hurdles in manufacturing, in the way modifying a chassis to make space for an FCM would be. A requirement is however that main hydraulic and pneumatic connection shall not interfere in vertical and horizontal direction, to facilitate deployment of manifolds when installing multiple FCMs.

The areas identified are, as illustrated in figure 3:

- an area on the form factor's longer side, starting with a corner and at most 340 mm long;
- an area on the form factor's shorter side, of any length up to the full width of the unit.

The depth of this area is not strictly defined, but must be sufficient so that all connectors be within the main form factor *when connected*.

Preferably only one interface area should be used, but if two are employed they must be mechanically redundant (all pneumatic and hydraulic connections on both areas). Also, one of the two areas will be required to have a sufficient depth so that all connectors are within the main form factor *when disconnected*.

Note that drain, ventilation, electric connections and I/O communications can be positioned anywhere within the form factor. The shape of high-voltage (HV) and low-voltage (LV) connectors are not specified, but the LV connector should withstand at least 100 A; this may for example be integrated within the I/O connector or implemented with cable lugs.

The standard also specifies acceptable ranges for the inner diameter of pipes and hoses for inlet hydrogen and air, outlet steam, drain, and cooling. These increase with FCM nominal power, and are provided as metric ranges that also span commercially common Imperial units.

The standard also sets some requirements for handling of environmental conditions: the FCM shall be able to operate between −25 °C and 45 °C, up to an altitude of 3000 m (with some derating allowed), output voltage between 160 V and 850 V and hydrogen input pressure between 6 bar and 22 bar.

IV. Digital Interface

The digital interface shall enable control of the FCM operation e.g. state changes and setpoints, as well as diagnostic and fault messages and sensor information. There is no existing standard for communication between an FCM and the application system, but it is preferable to build upon existing standards to the largest extent possible. Due to its prevalence in the automotive sector and present usage by several FCM suppliers, CAN bus is chosen as the low-layer protocol; the more recent CAN-FD is supported as an option. While other technologies such as FlexRay may be relevant for the automotive industry, Ethernet is the most useful for other application areas such as maritime and to be future-proof. Ethernet has the benefit of higher transmission capacity and network size, and with the development of automotive Ethernet standards it has a potential for increased use also in automotive applications [3]. Therefore, the protocol is also implementable over Ethernet with IP and either TCP or UDP as transport protocol. The higher-level layer is implemented, as customary for HD applications, with SAE J1939 by modelling the FCM as a motor-generator set and re-purposing the most suitable messages.

As it is expected that several applications may employ multiple FCMs, the standard allows both hosting them all on the main CAN bus, or using a single primary FCM as gateway to the other secondary FCMs (daisy-chain). In case the DC/DC converter is not included in the FCM, the digital interface allows letting the FCM control an external DC/DC converter.

The StasHH standard has taken input from an analysis of the regulations, codes and standards for safety of fuel cell systems [7] in different applications to derive safety related requirements. The protocol has provisions for emergency stops (hardwired and as signal), high-voltage interlock loop (HVIL), cybersecurity and diagnostics. For the control of the FCM operation six states have been defined (Idle, Standby, Starting, Running, Stopping and Error) as illustrated in figure 4. In addition, to provide further flexibility it is possible to define additional sub-states that may be added by manufacturer as proprietary extensions.

The standard does not directly specify a connector to avoid lock-in to a single vendor as well as to provide flexibility for different application requirements. However, it does prescribe 5 mandatory pins, 9 optional ones, and recommends to include another 4 for future extensions.

V. Future Work

The standard was published on stashh.eu in early 2022, and FCM suppliers have started building their units to be tested from 2023; several partners are already close to completing their FCMs.

At the end of 2022 the project will publish a market assessment for the deployment of StasHH-compliant FCMs; at the end of 2023 a techno-economic analysis quantifying the approach's advantages will be published.

A report from the OEM perspective will establish best practices for integration of the standard in current and new designs; the participation of OEMs from multiple domains will ensure the relevance and interdisciplinarity of the report.

In 2023 a demonstration of an HD vehicle equipped with a StasHH FCM is planned, in a genset installed in a non-road

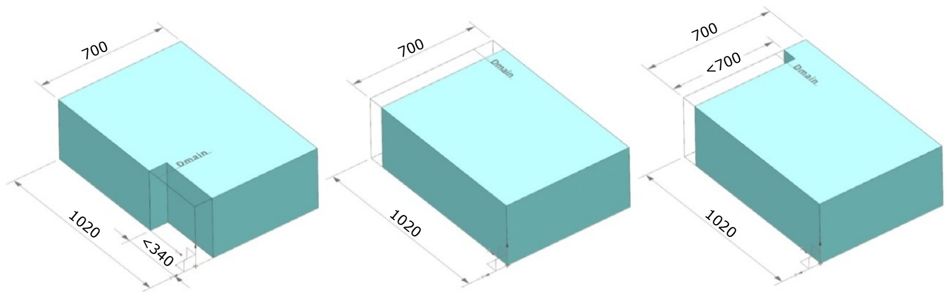

Fig. 3. The possible interface areas for a StasHH FCM, an A-type in this example. From left, either the side corner, the full front, or part of the front.

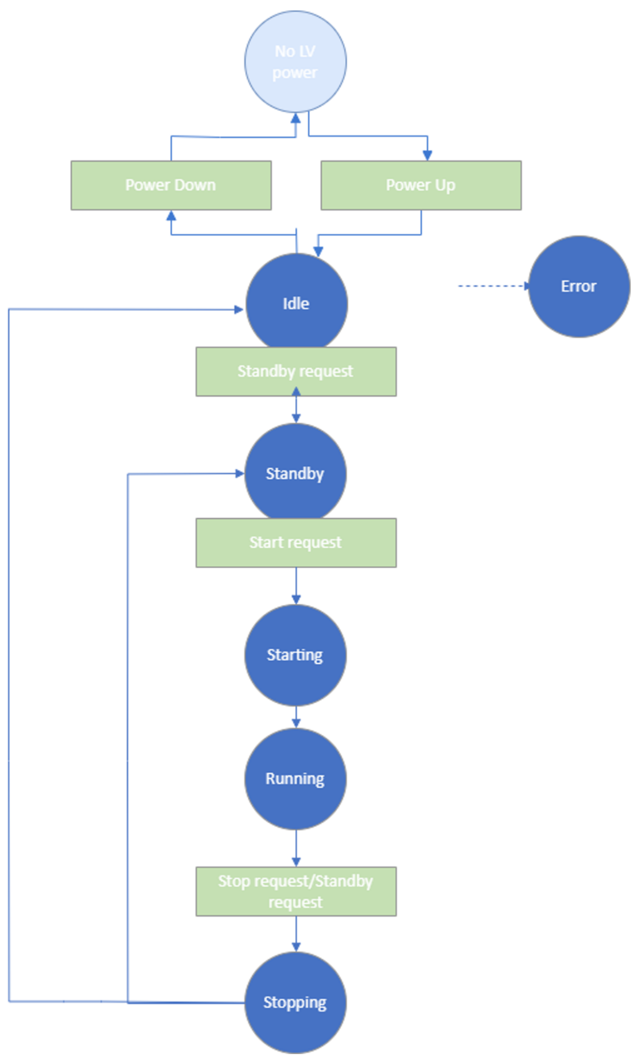

Fig. 4. Minimal state machine of a StasHH FCM.

vehicle. This will give further exposure to the standard and prove its feasibility for quick deployment even in niche HD applications.

Most importantly, the standard will be updated by the end of the project (mid-2024) considering the feedback from FCM suppliers, OEMs, other project partners, and external observers.

VI. Conclusion

The StasHH project has produced a practical FCM standard together with some of the most important FC suppliers worldwide and a representative slice of heavy-duty OEMs. The form factors were designed close to the requirements of European trucks, as they are both a large market and a sector with particularly demanding size requirements, but adapt well to a wide range of heavy-duty applications. The standard also specifies interfaces for the flow of fuel, air, water, coolant and information between the module and the host vehicle. Currently, eight major FCM manufacturers are building their StasHH-compatible modules, which they will have tested in 2023 and will soon become available on the market.

The StasHH project is now disseminating the standard, promoting its adoption, and looking for feedback from both industry and academia. Interested parties can join our exploitation group at no cost and influence the further development of the final version of the standard.

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